

# The Story Behind a Half recent BNL contributions to QCD Spin Physics

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# Involvement of BNL Nuclear Theory group

## Perturbative QCD and the Spin/Flavor Structure of Hadrons

is one of the main thrusts of our Physics program

### Senior Staff

#### Jianwei Qiu

QCD corrections, factorization,  
transverse spin phenomena, quarkonium, ...

#### Marco Stratmann

QCD corrections, global QCD analyses, heavy quarks,  
hadronization, ...

### Post-doctoral Fellows

#### Martin Hentschinski

QCD corrections, small-x, evolution, ...

#### Yan-Qing Ma

QCD corrections, factorization, quarkonium, ...

tightly connected to existing and planned experimental programs at RHIC

close ties to RHIC Spin Collaboration (PHENIX, STAR)

participating in EIC Task Force @ BNL

very active network of collaborators

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# the cookies we crumble: fundamental questions driving spin physics



## how do quarks and gluons carry the proton spin

$$\Delta f \equiv \text{Diagram} - \langle P, \frac{1}{2} | \mathcal{O}_{q,\bar{q},g} | P, \frac{1}{2} \rangle$$

The diagram shows two red circles representing quarks. The left circle has a white dot in the center with a yellow arrow pointing clockwise, and a green arrow pointing to the right. The right circle has a white dot in the center with a yellow arrow pointing counter-clockwise, and a green arrow pointing to the right.

- what are the best probes to extract helicity PDFs
- what is the role of orbital angular momentum
- factorization in spin-dependent processes
- how does it compare to models/lattice QCD



# the cookies we crumble: fundamental questions driving spin physics



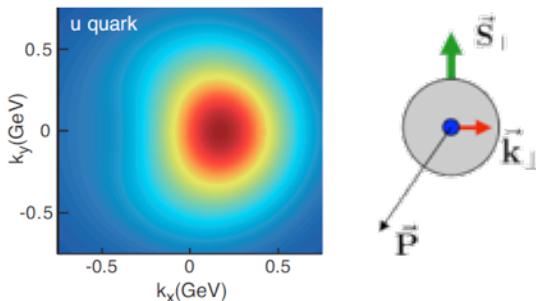
## how do quarks and gluons carry the proton spin

$$\Delta f \equiv \text{Diagram of two quarks with arrows indicating spin} - \langle P, \frac{1}{2} | \mathcal{O}_{q,\bar{q},g} | P, \frac{1}{2} \rangle$$

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## reveal mechanisms behind transverse spin phenomena



- further develop TMD framework / evolution
- explore connections to unintegrated PDFs
- role of multi-parton correlations & their matching to TMD's



# the cookies we crumble: fundamental questions driving spin physics



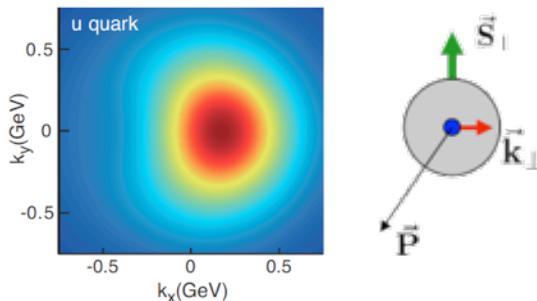
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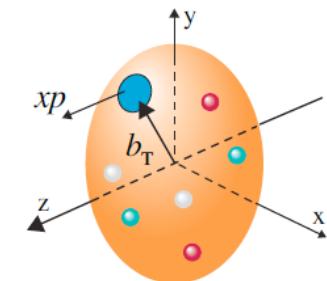


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## what is the distribution of partons in the transverse plane

- physics of exclusive processes & generalized parton distributions
- possible access to quark and gluon angular momentum
- high-level connections of TMDs & GPDs to Wigner functions





# the cookies we crumble: fundamental questions driving spin physics



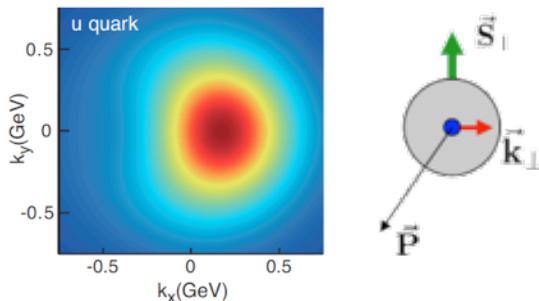
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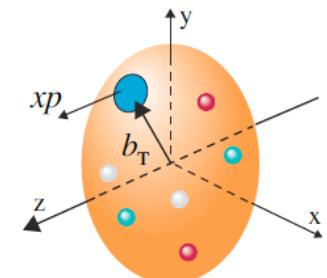


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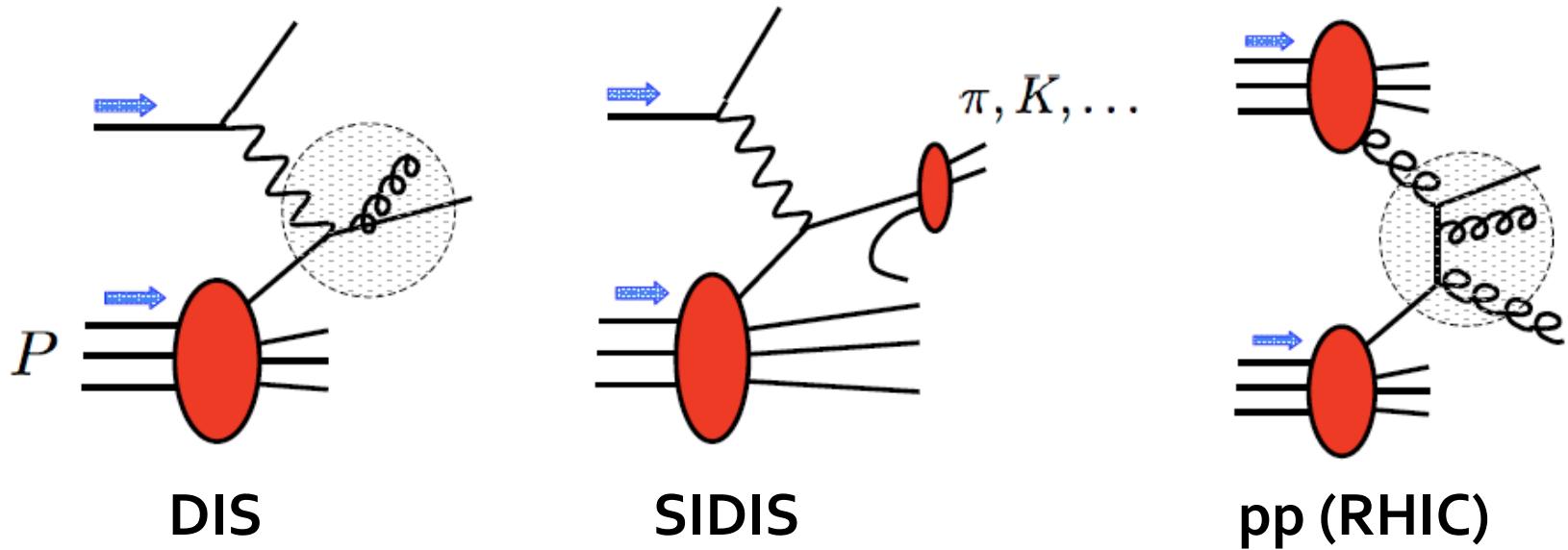


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# the probes of nucleon helicity structure



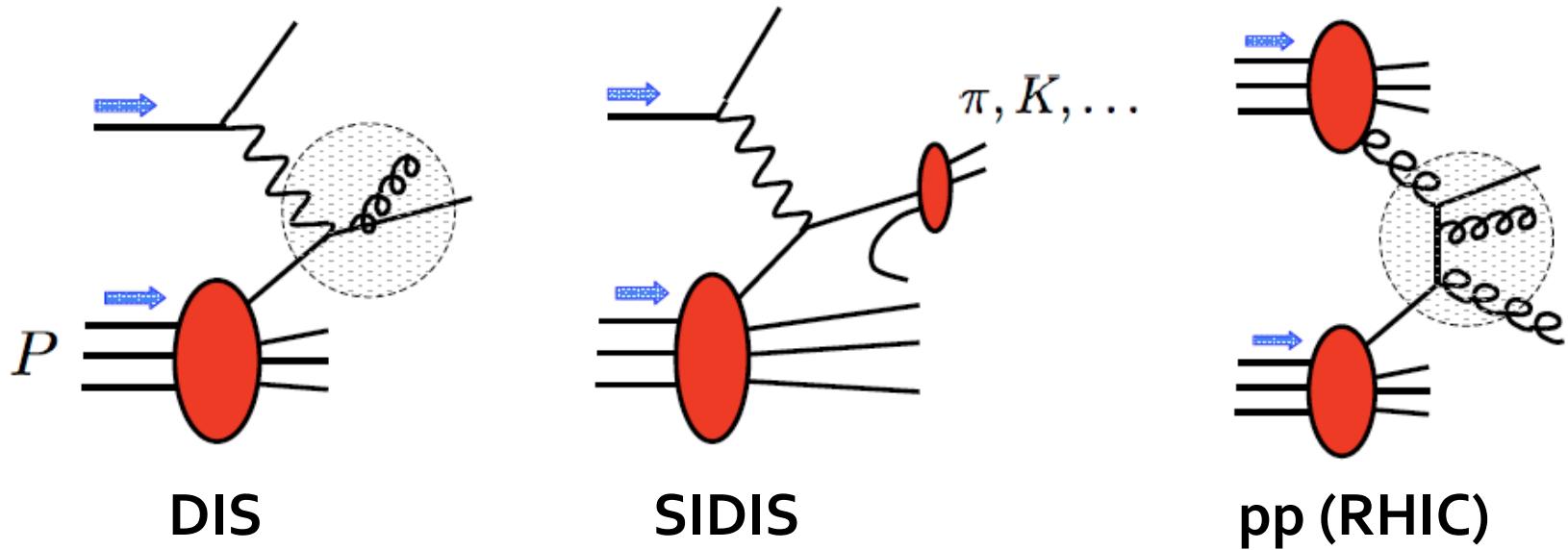
guiding principle: **factorization**

e.g. **DIS**  $d\Delta\sigma = \sum_{f=q,\bar{q},g} \int dx \Delta f(x, Q^2) d\Delta\hat{\sigma}_{\gamma^* f}(xP, \alpha_s(Q^2))$

essential: work out QCD corrections  $d\Delta\hat{\sigma} = d\Delta\hat{\sigma}^{\text{LO}} + \alpha_s d\Delta\hat{\sigma}^{\text{NLO}} + \dots$

better control of theoretical (scale) uncertainties

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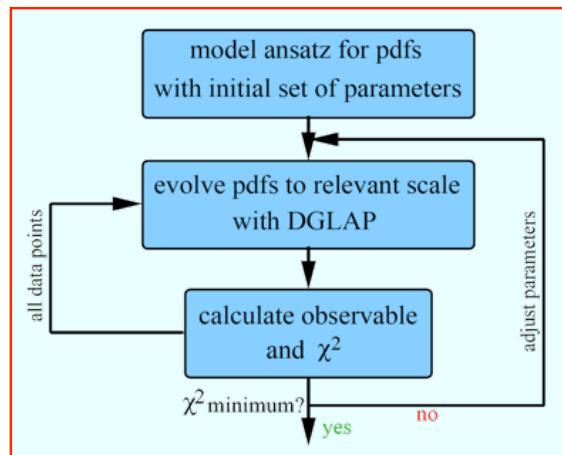
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better control of theoretical (scale) uncertainties

resulting PDFs: synergy of different probes (a way to test factorization)

# anatomy of global QCD analyses

obtain helicity PDFs  
through global  $\chi^2$  optimization



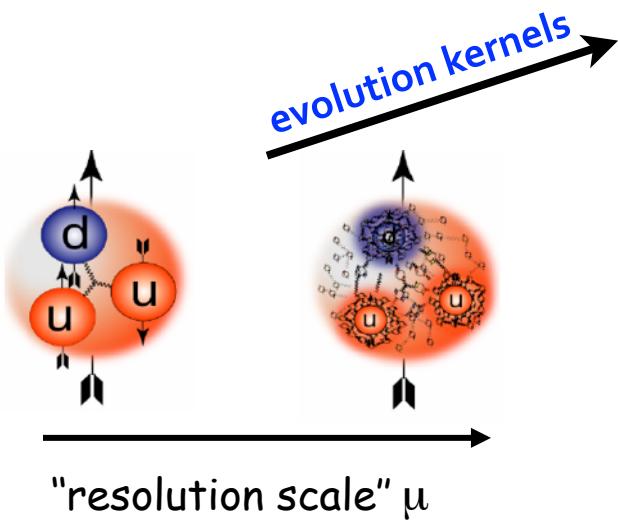
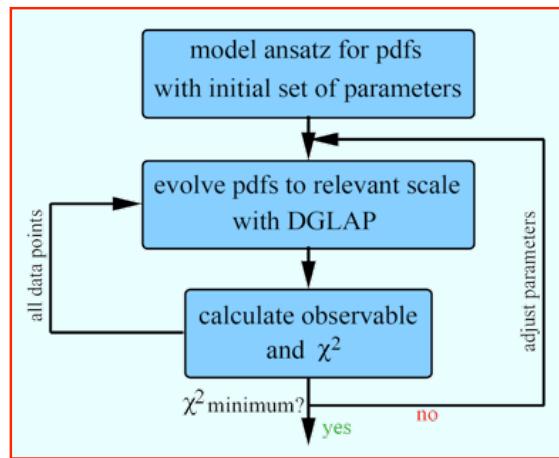
set of optimum parameters  
for *assumed* functional form

**computational challenge:**

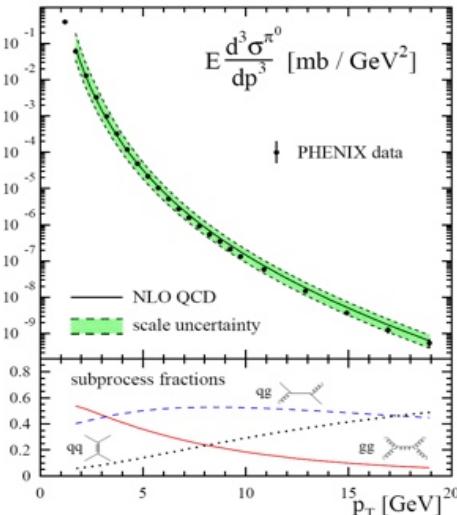
- up to O(20-30) parameters
- many sources of uncertainties
- very time-consuming NLO expressions

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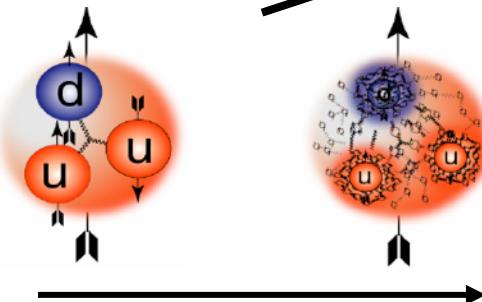
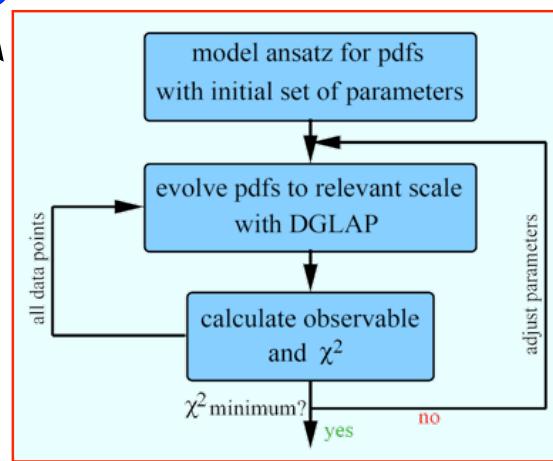


# anatomy of global QCD analyses



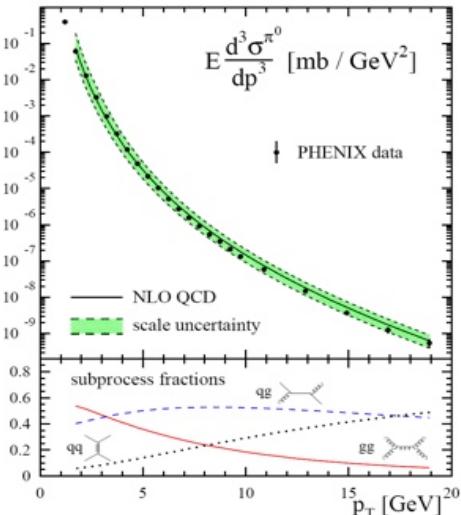
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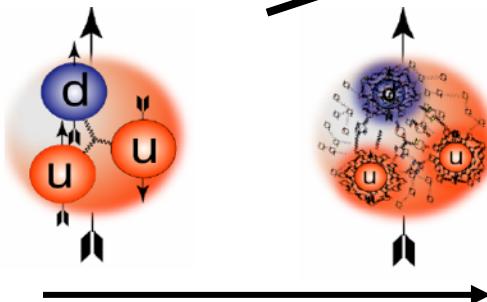


Mertig, van Neerven; Vogelsang; ...

# anatomy of global QCD analyses

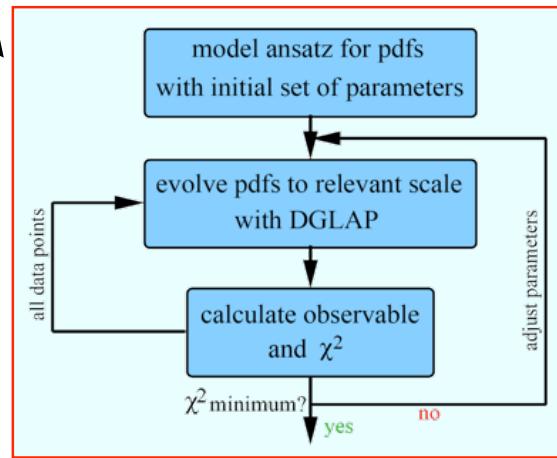


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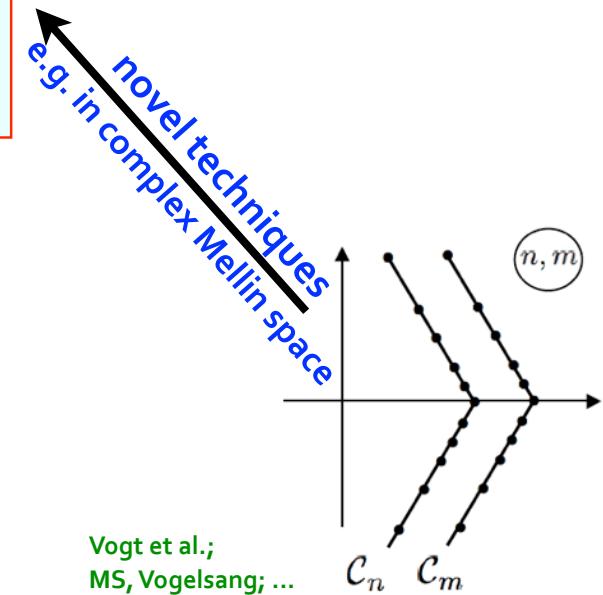


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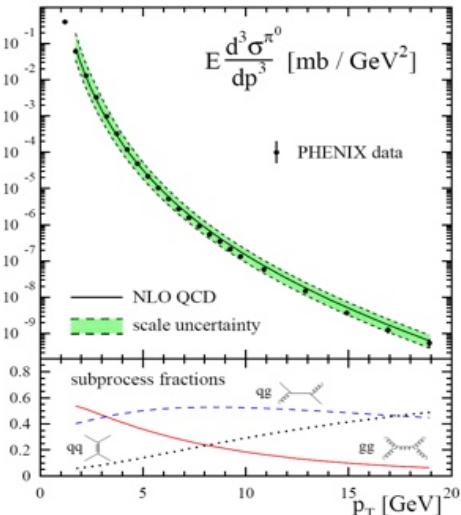
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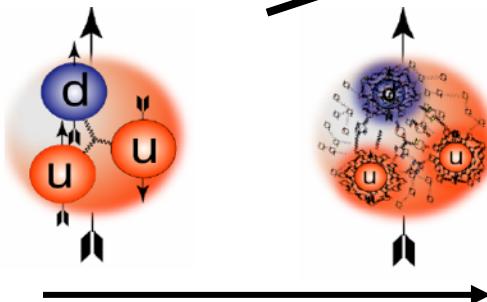
"resolution scale"  $\mu$



# anatomy of global QCD analyses



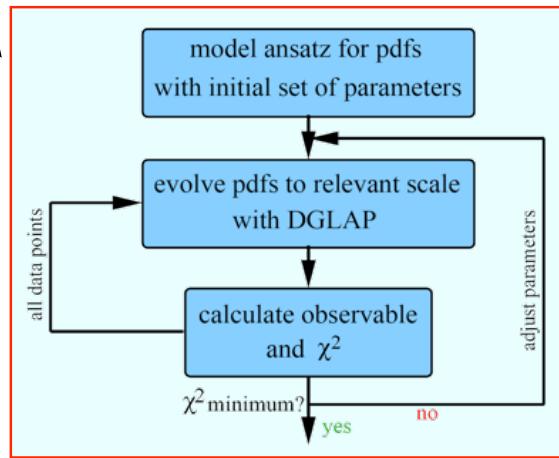
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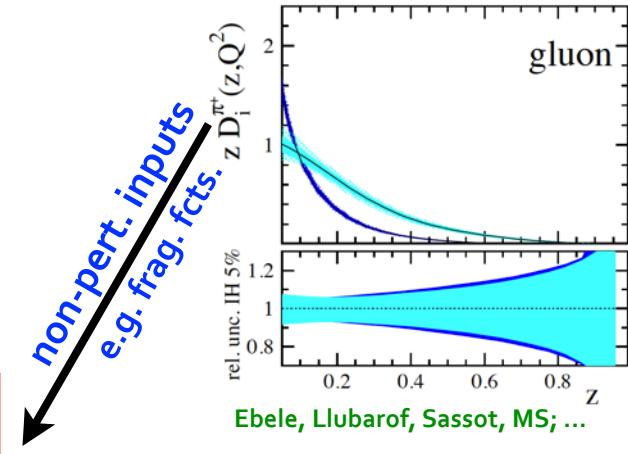
Mertig, van Neerven; Vogelsang; ...

cross sections at NLO

obtain helicity PDFs  
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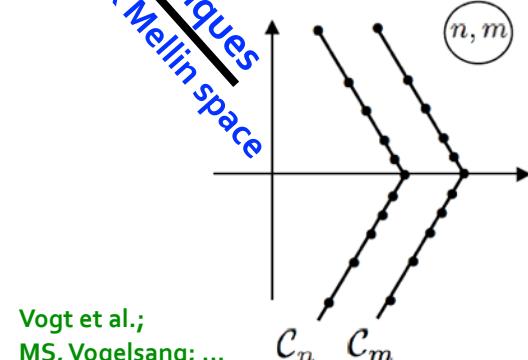


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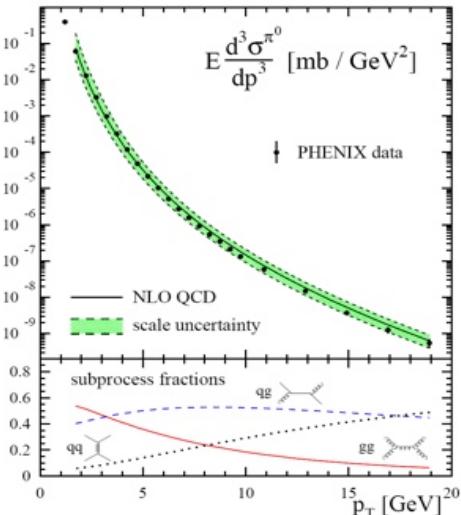
non-pert. inputs  
e.g. frag. fcts.

novel techniques  
e.g. in complex Mellin space

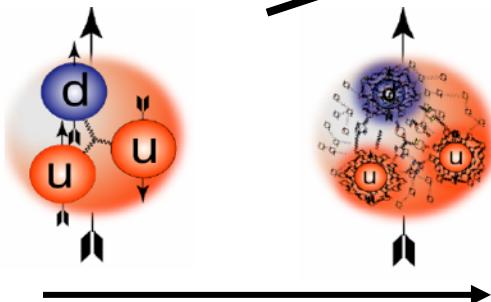


Vogt et al.;  
MS, Vogelsang; ...

# anatomy of global QCD analyses



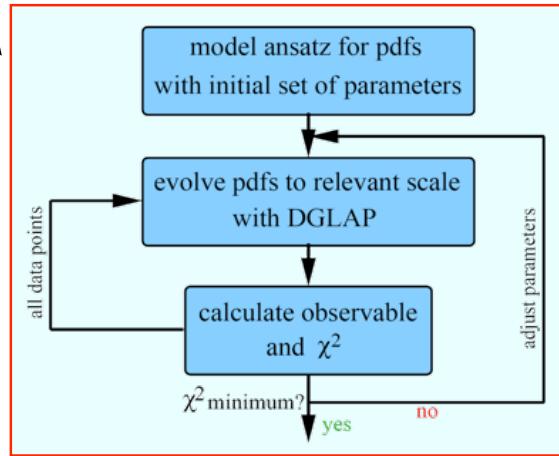
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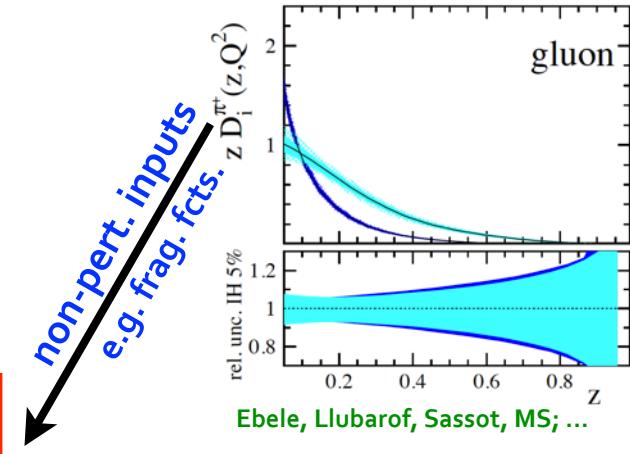
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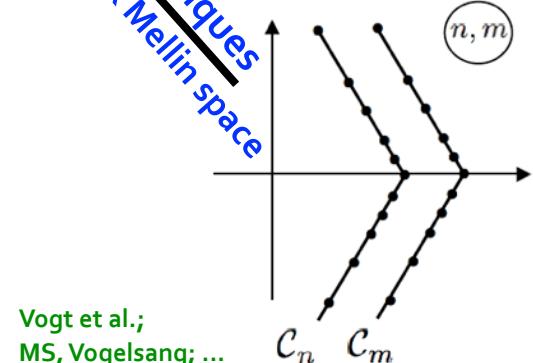
set of optimum parameters  
for assumed functional form

plus a prescription to  
estimate & propagate  
**uncertainties**



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e.g. frag. fcts.

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e.g. in complex Mellin space

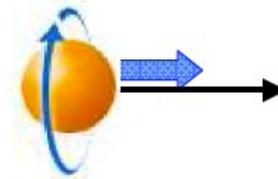
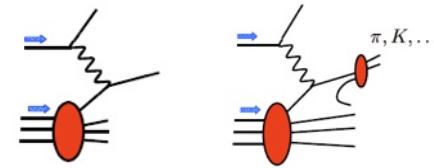


# what did we learn about the proton spin?

for many years very little progress despite very active experimental programs: >25 yrs. of pol. (SI)DIS  
SLAC, CERN, DESY, JLab

emerging spin budget of the nucleon:

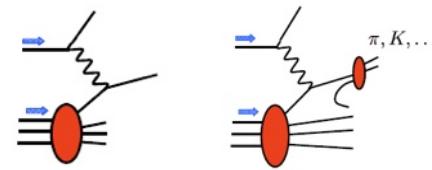
$$\frac{1}{2}\hbar$$



$$\frac{1}{2} = \langle P, \frac{1}{2} | \hat{J}_z | P, \frac{1}{2} \rangle$$

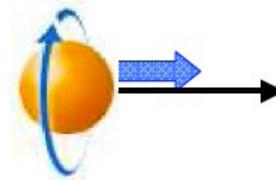
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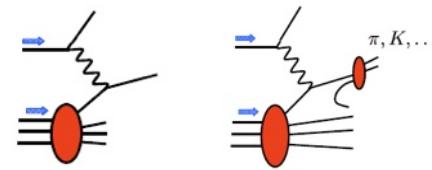


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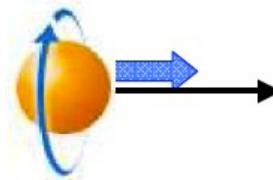
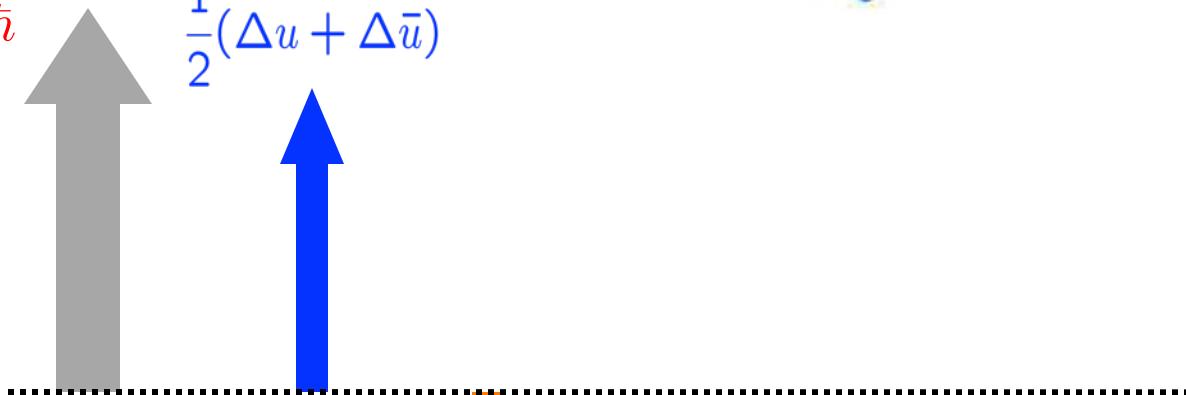
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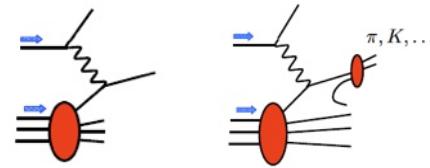
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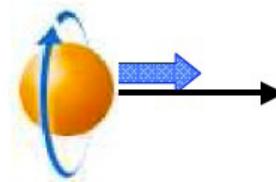
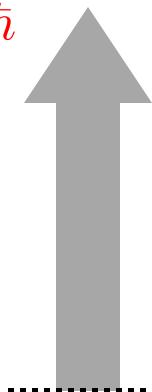
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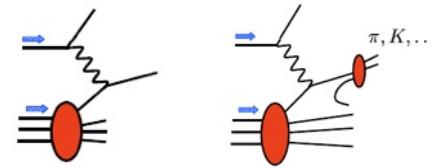
$$\frac{1}{2}(\Delta s + \Delta \bar{s})$$



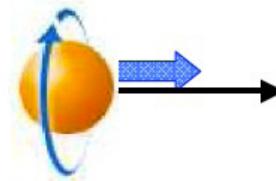
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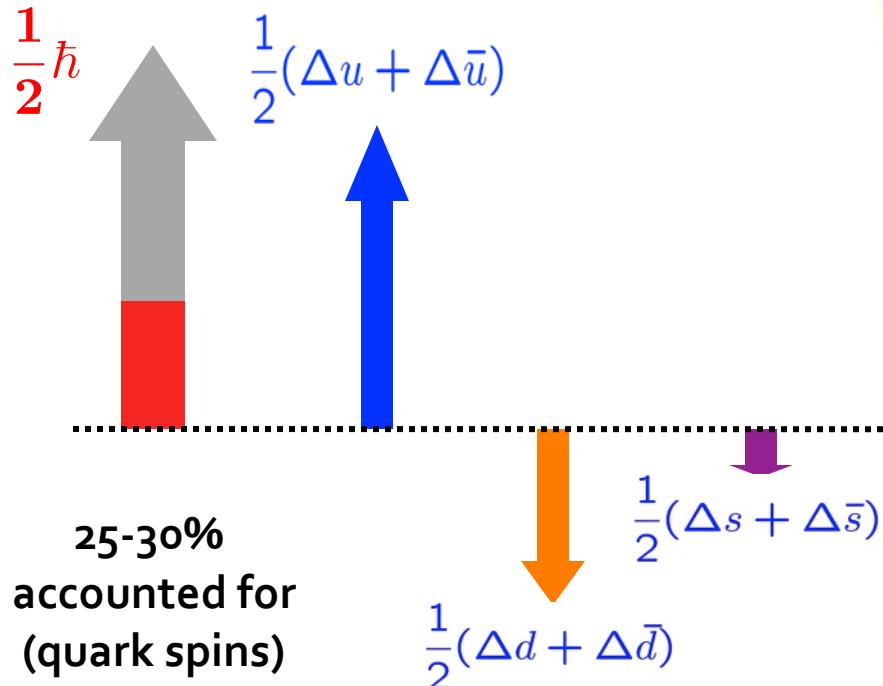
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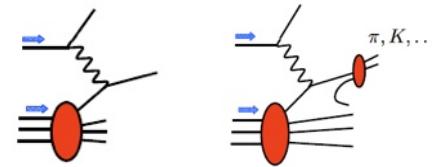


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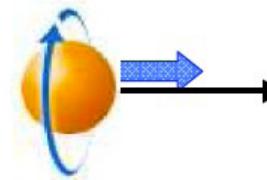


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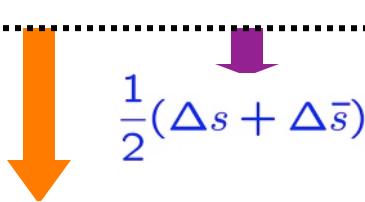
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$$\frac{1}{2}\hbar$$
  
$$\frac{1}{2}(\Delta u + \Delta \bar{u})$$

$$\Delta g \quad L_q + L_g$$

25-30%  
accounted for  
(quark spins)

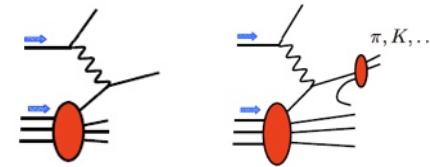

$$\frac{1}{2}(\Delta s + \Delta \bar{s})$$
  
$$\frac{1}{2}(\Delta d + \Delta \bar{d})$$

?

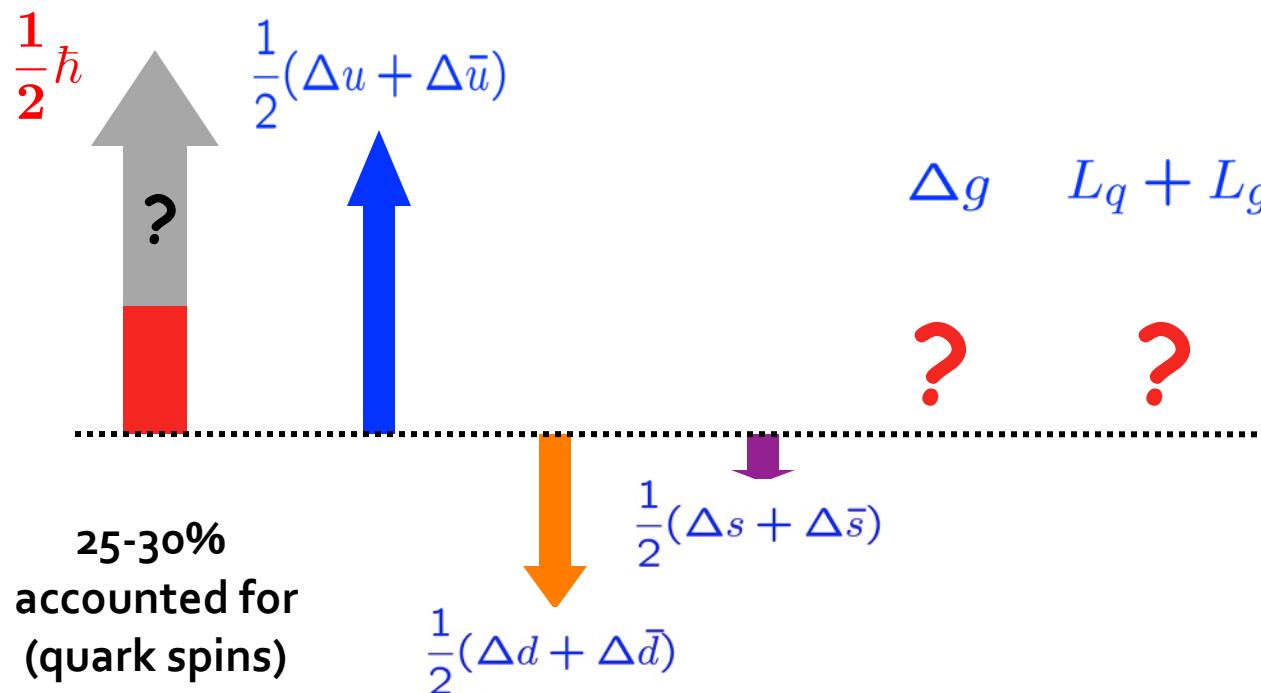
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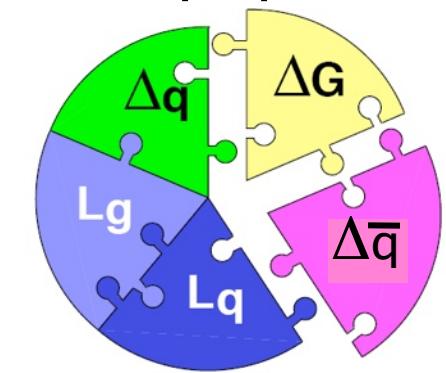
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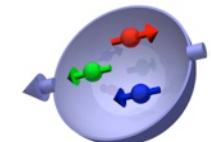


the “spin puzzle”



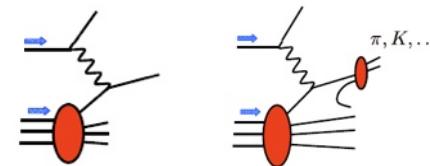
recall:  
naïve quark model

$$\Delta \Sigma = 1$$

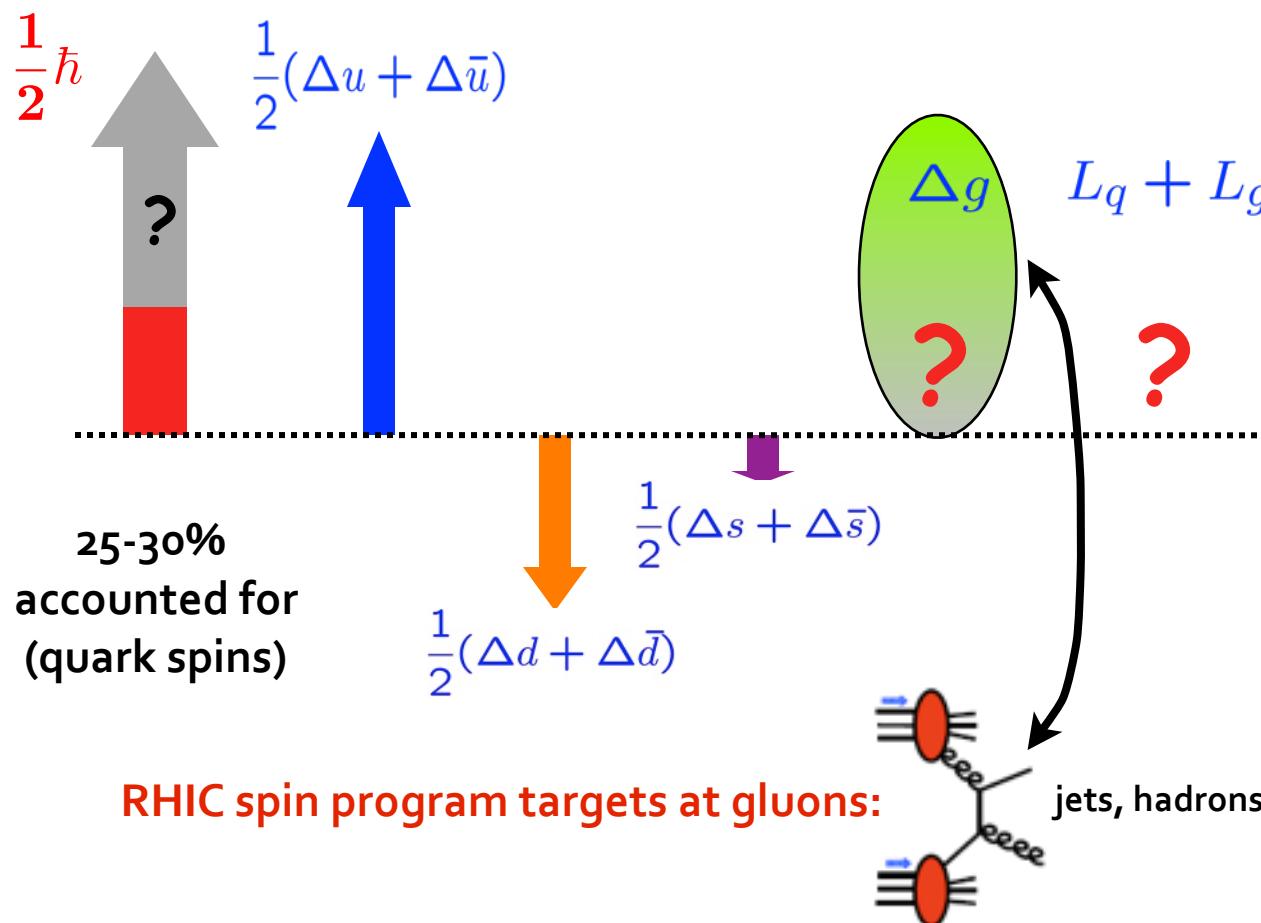


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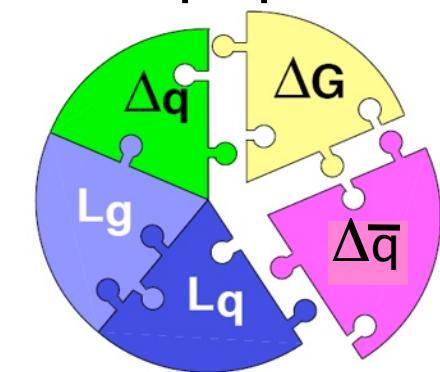
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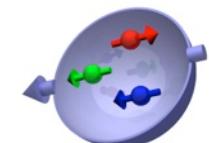


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# impact of “1<sup>st</sup> generation” RHIC data on $\Delta g$

**DSSV:** 1<sup>st</sup> global QCD analysis of polarized (SI)DIS & pp data

de Florian, Sassot, MS, Vogelsang; PRL [101](#) (2008) 072001; PR D[80](#) (2009) 034030

- consistently performed at NLO (no K-factor cheating)
- estimates of uncertainties

recall:



$$\Delta \mathbf{f}(\mathbf{x}) \equiv \mathbf{f}_{\rightarrow}^{\text{green}}(\mathbf{x}) - \mathbf{f}_{\leftarrow}^{\text{red}}(\mathbf{x})$$

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recall:



$$\Delta f(x) \equiv f_{\rightarrow}(x) - f_{\leftarrow}(x)$$

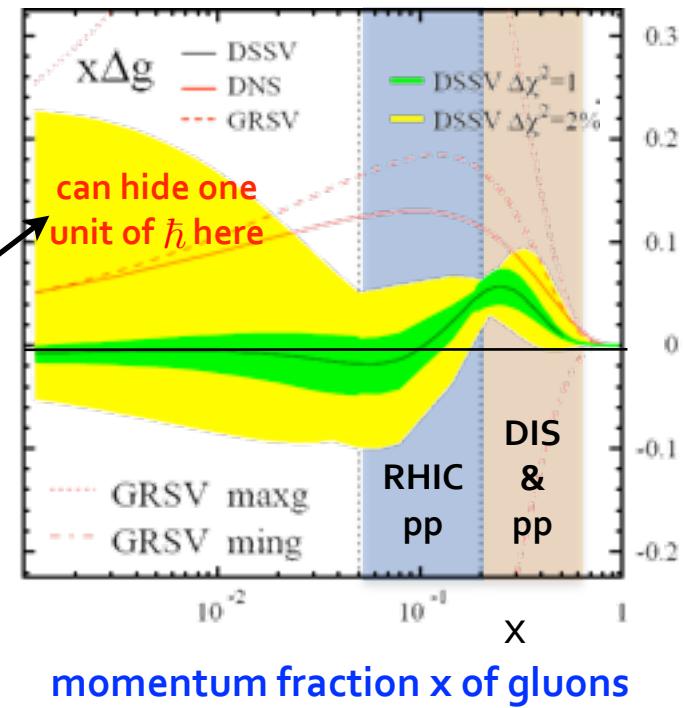
### main results:



$\Delta g(x, Q^2)$

- found to be small at  $0.05 < x < 0.2$  [from RHIC data]  
still significant uncertainties

yet, small  $x$  behavior completely unconstrained  
(determines  $x$ -integral which enters proton spin sum)



# impact of “1<sup>st</sup> generation” RHIC data on $\Delta g$

## DSSV: 1<sup>st</sup> global QCD analysis of polarized (SI)DIS & pp data

de Florian, Sassot, MS, Vogelsang; PRL 101 (2008) 072001; PR D80 (2009) 034030

- consistently performed at NLO (no K-factor cheating)
- estimates of uncertainties

recall:



$$\Delta f(x) \equiv f_{\rightarrow}(x) - f_{\leftarrow}(x)$$

### main results:



$\Delta g(x, Q^2)$

- found to be small at  $0.05 < x < 0.2$  [from RHIC data]  
still significant uncertainties

yet, small  $x$  behavior completely unconstrained  
(determines  $x$ -integral which enters proton spin sum)



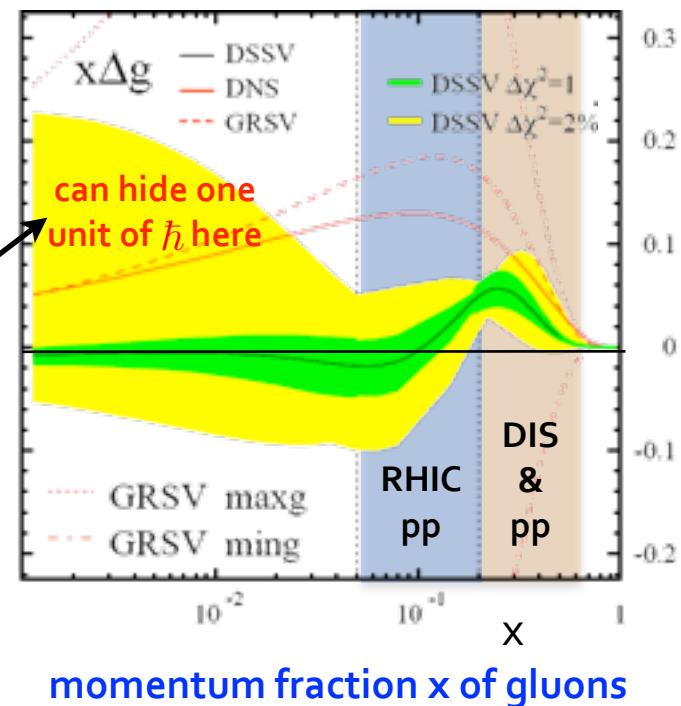
$\Delta q's(x, Q^2)$

- indications for non-trivial sea polarizations [from SIDIS data]

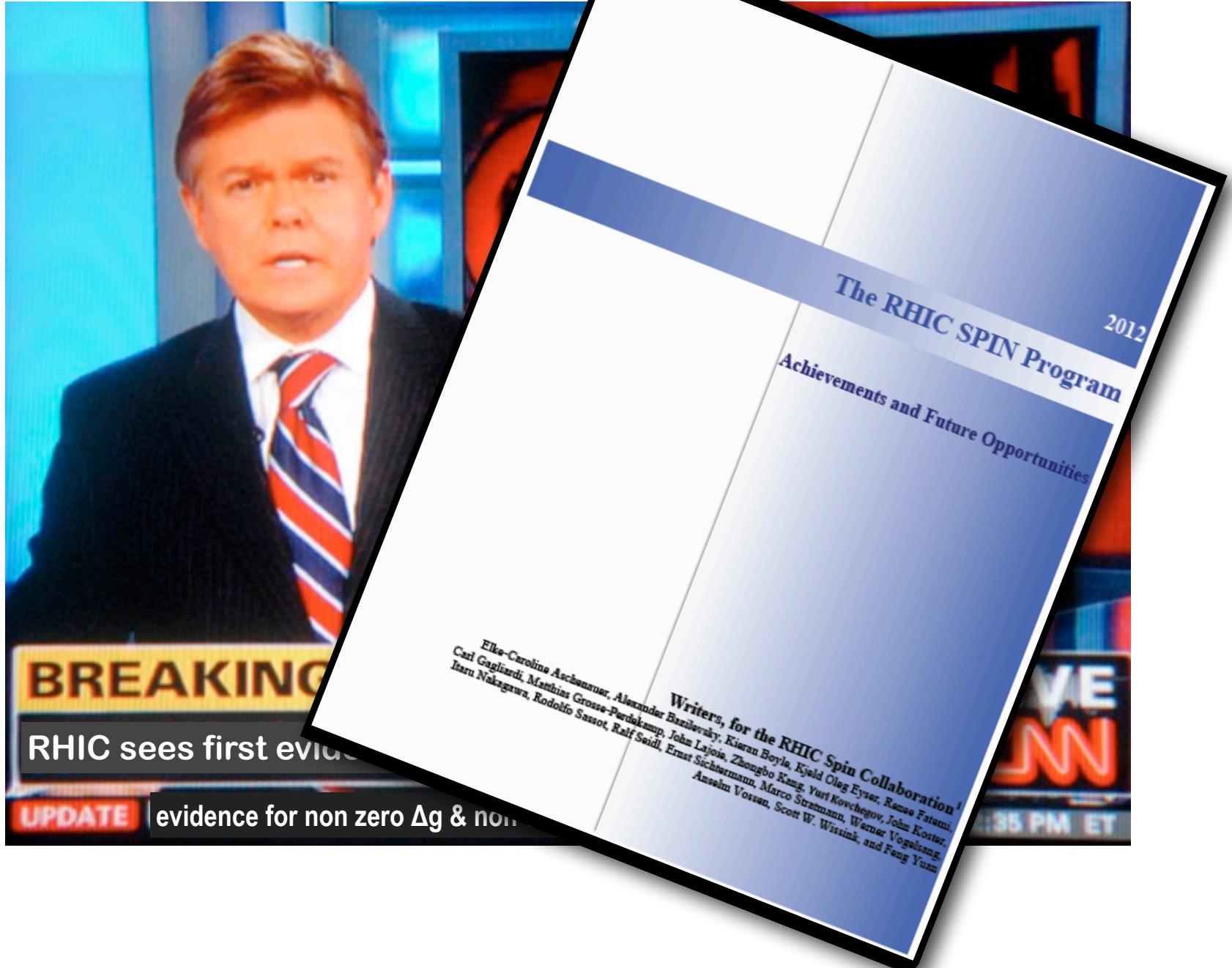
$$\Delta \bar{u} > 0 \quad \Delta \bar{d} < 0$$

- unexpectedly small strangeness pol. [from SIDIS kaon data]

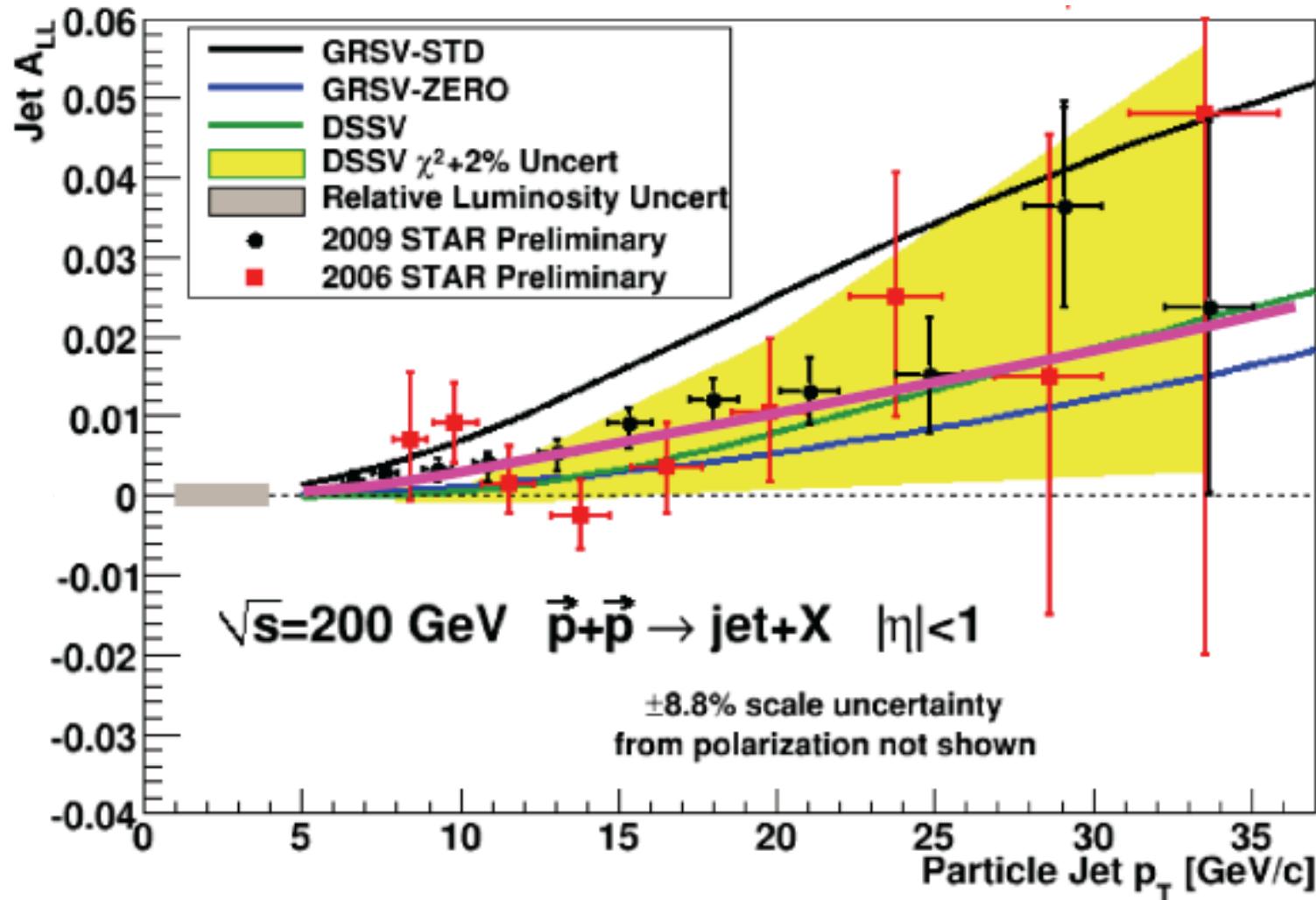
sizable SU(3) breaking? also seen on the lattice [Bali et al.](#), 0811.0807; 0911.2407; 1011.2194







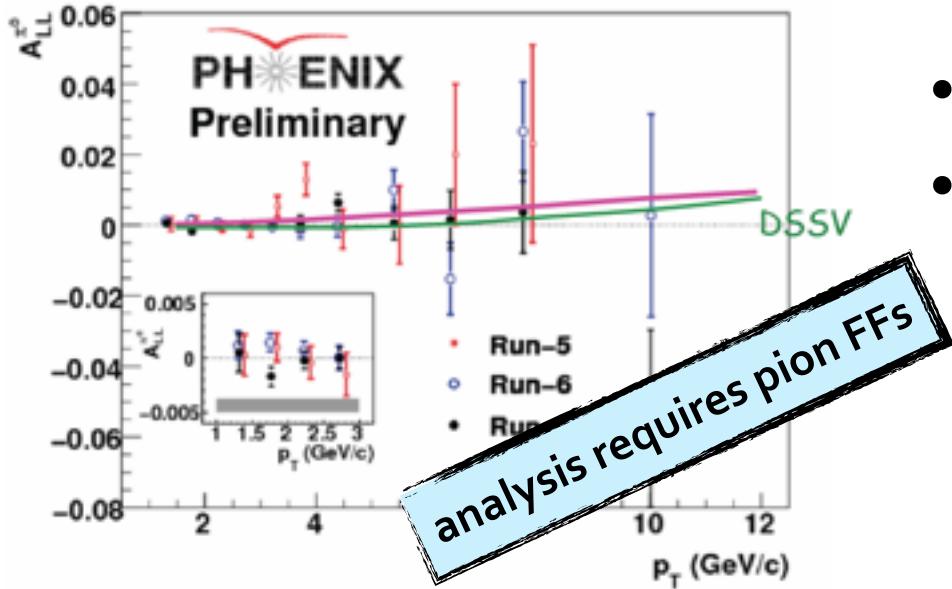
# new STAR run 9 jet data - impact on $\Delta g$ ?



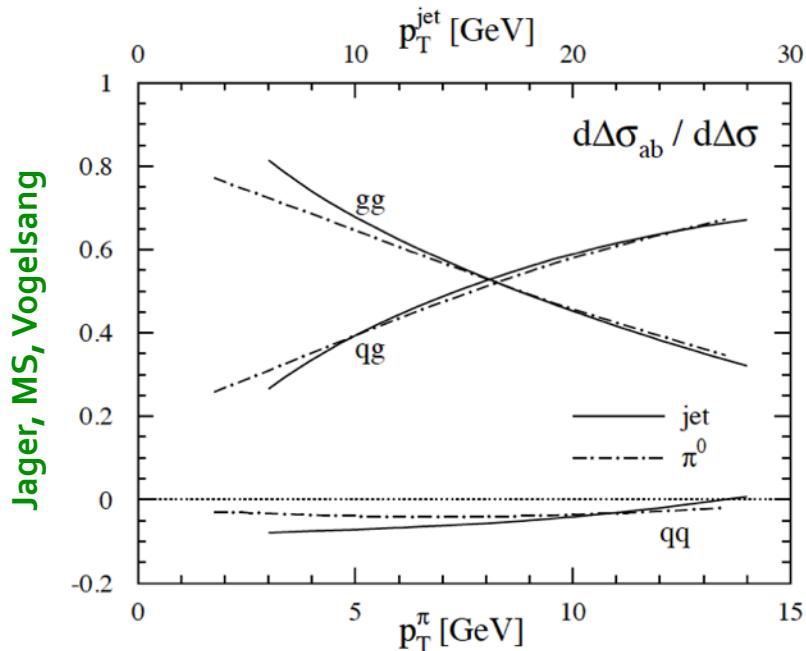
find:

gluon with  $\int_{0.05}^{0.2} \Delta g(x) dx \simeq 0.1$  fits well (approx. upper edge of our DSSV unc. band)

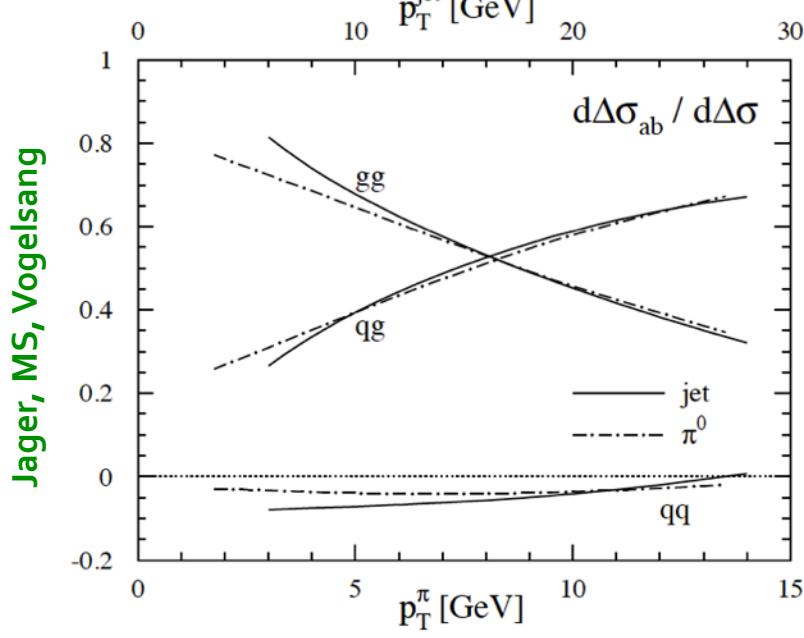
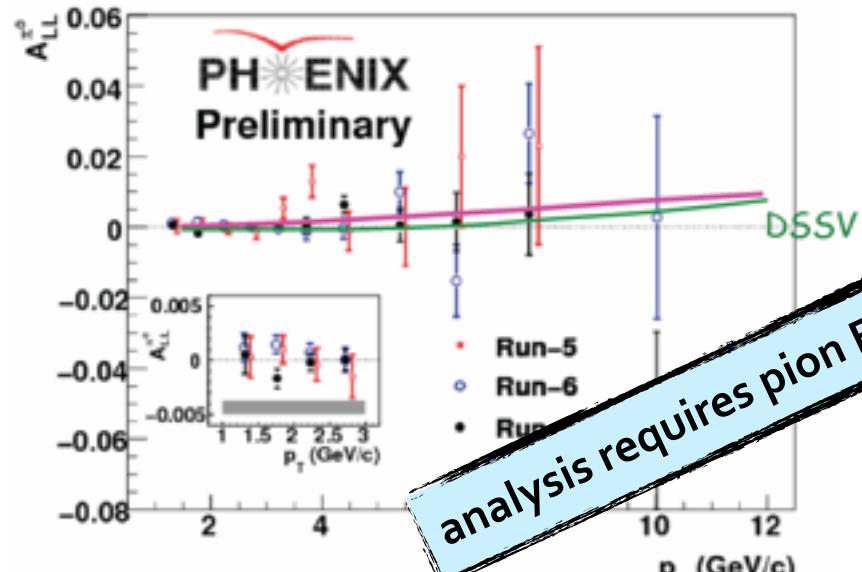
# consistency with new PHENIX $\pi^0$ data



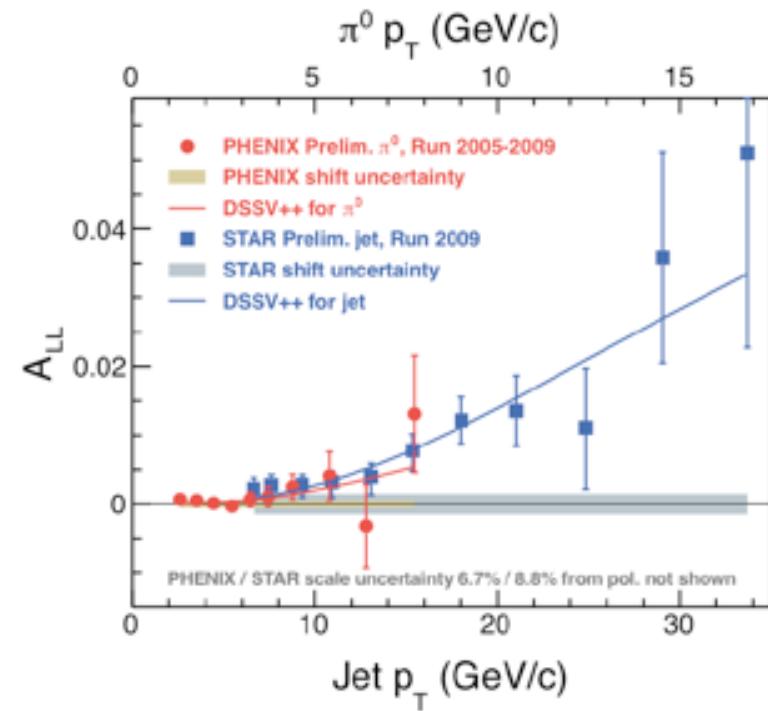
- mid rapidity  $\pi^0$  and jet data closely related
- $\pi^0$ 's carry approx. 1/2 of parton's momentum



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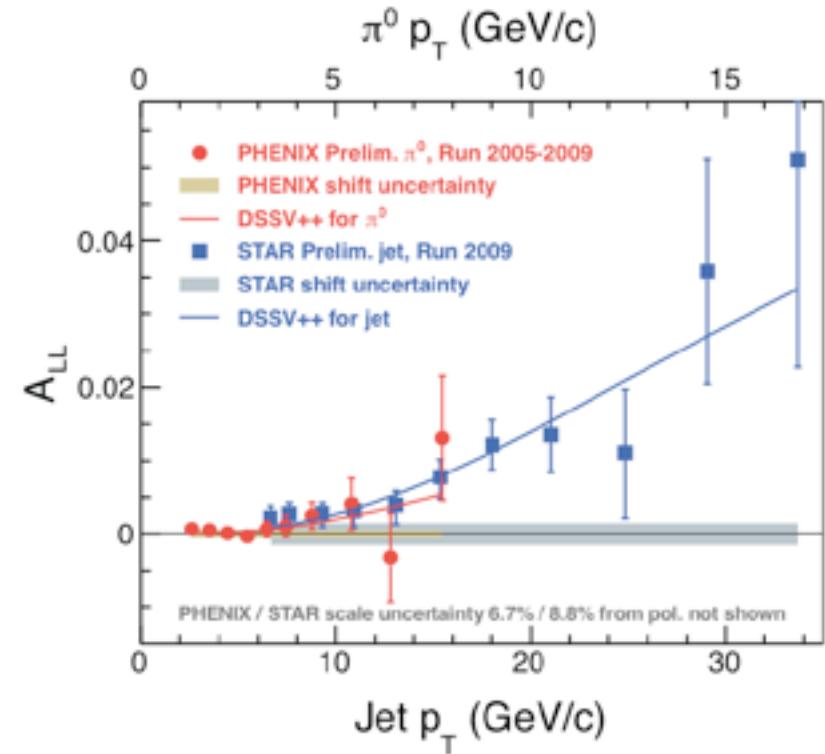


- mid rapidity  $\pi^0$  and jet data closely related
- $\pi^0$ 's carry approx. 1/2 of parton's momentum
- jet and  $\pi^0$  data can be put into one plot
- PHENIX probes lower  $p_T$  (slightly lower  $x$ )



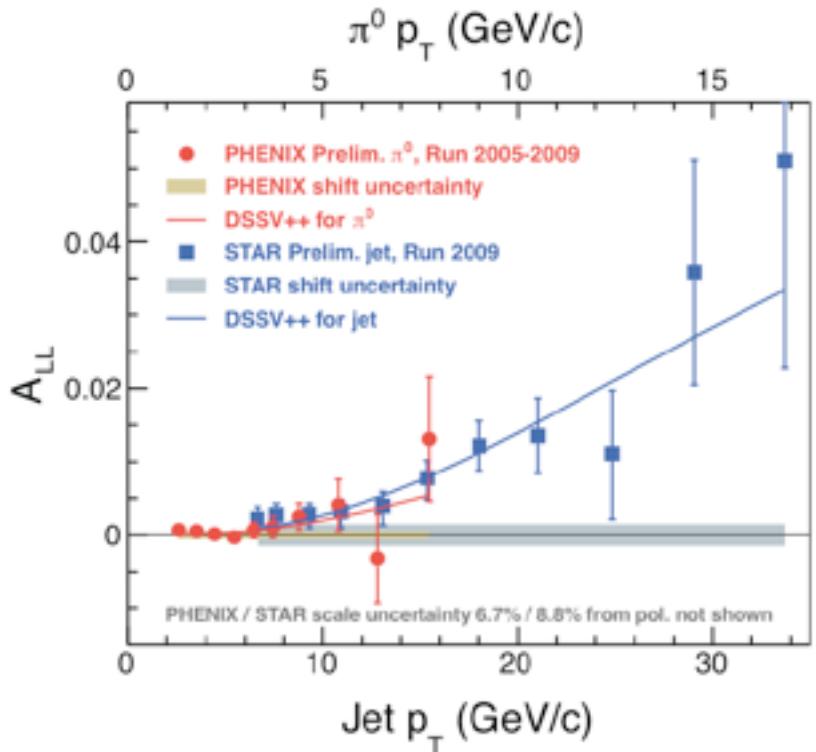
# re-analysis of helicity PDFs: DSSV -> DSSV++

RHIC run-9 data for jets and  $\pi^0$  included in DSSV++

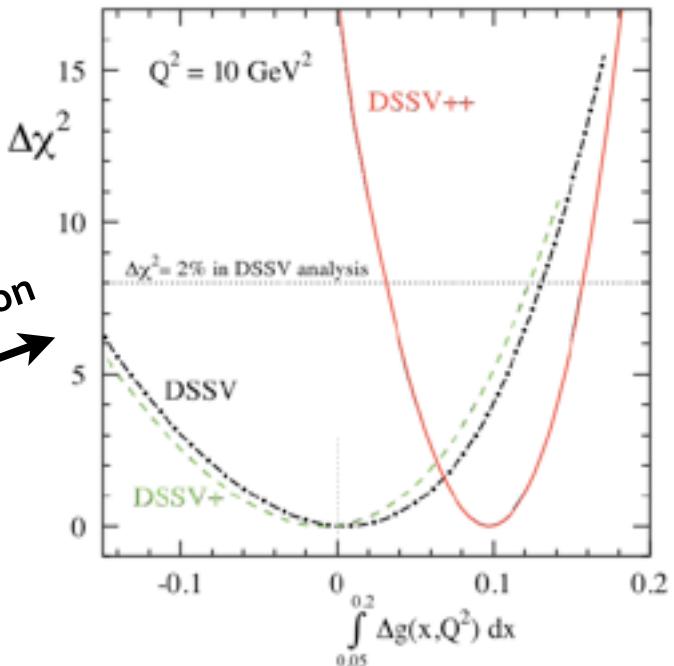


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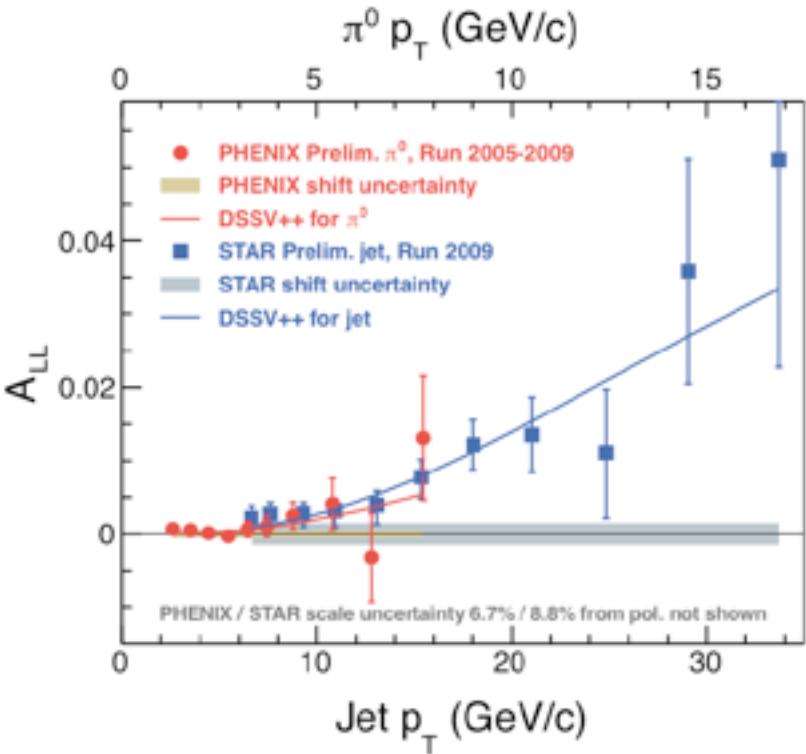


lead to non-zero  
 $\Delta g$  in RHIC x-region

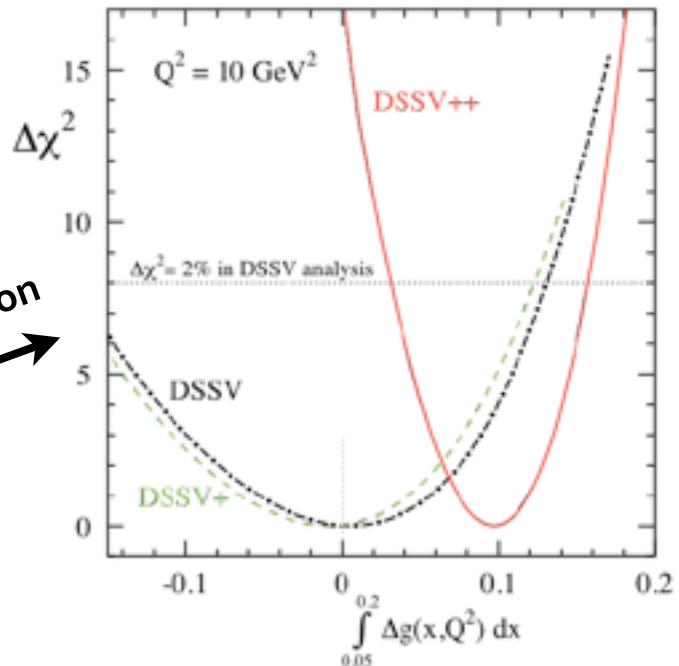


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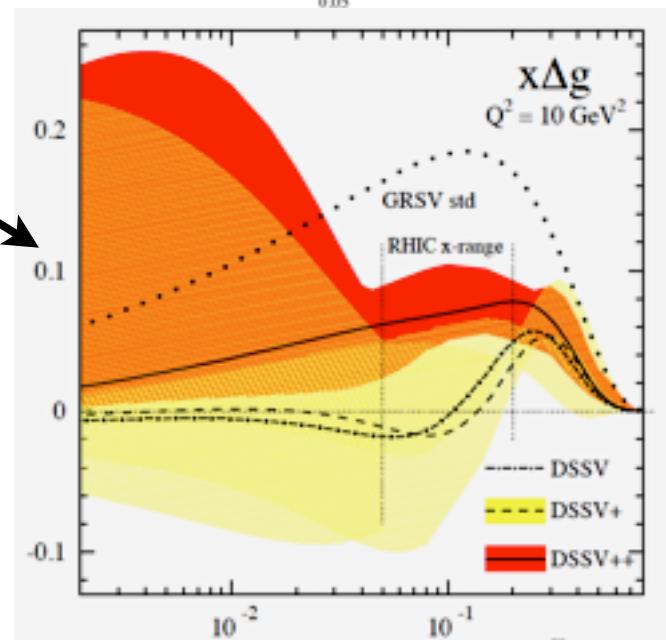
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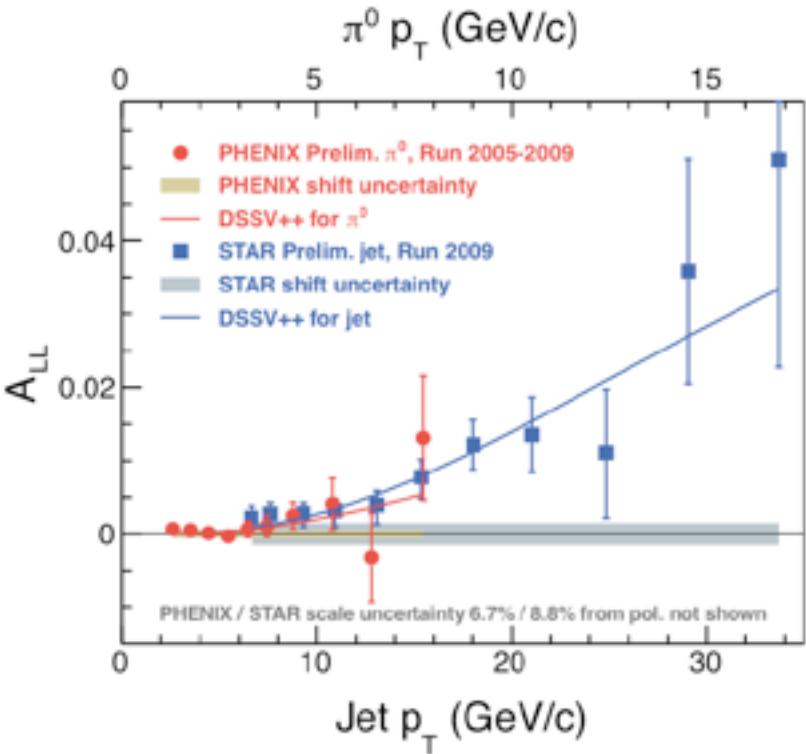


positive  $\Delta g$   
in RHIC  $x$ -region



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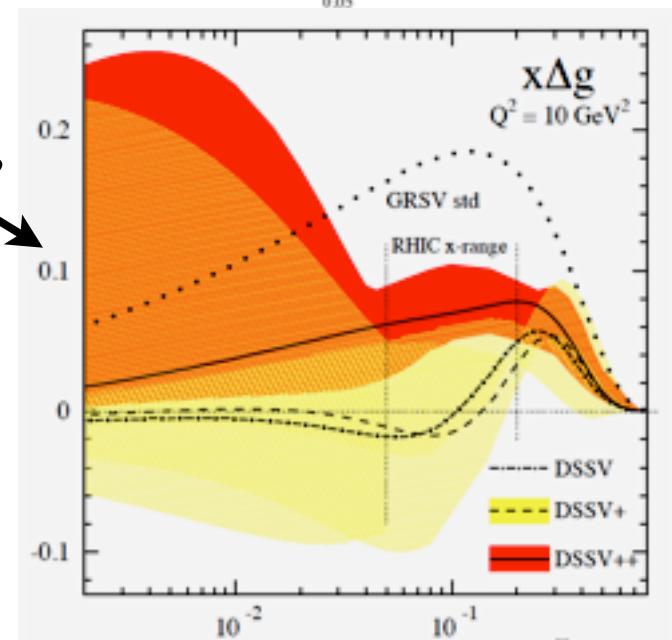
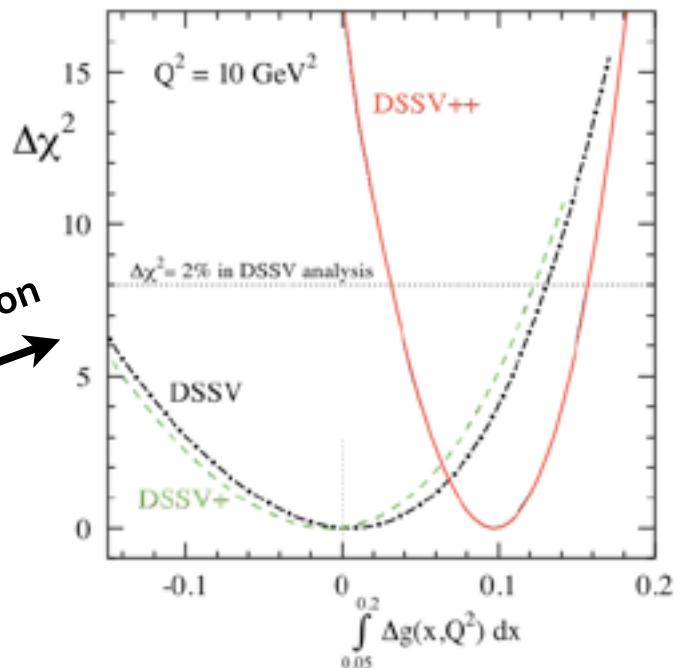


$$\int_{0.05}^{0.2} \Delta g(x, Q^2 = 10 \text{ GeV}^2) = 0.1 \pm 0.06 \pm 0.07$$

fully compatible with old DSSV error estimate  $0.005^{+0.129}_{-0.164}$

lead to non-zero  
 $\Delta g$  in RHIC  $x$ -region

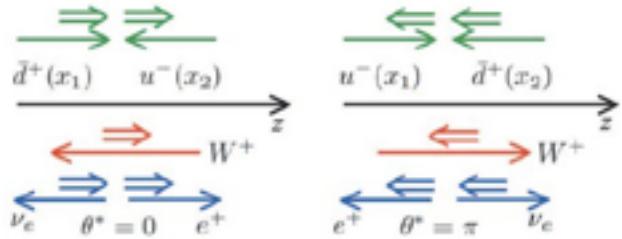
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# exciting new results also for W bosons

## key measurement at RHIC

- neat idea: parity-violating W's couple only to one parton helicity



study  
single spin  
asymmetries

$$A_L^{W^-} \approx -\frac{\Delta d(x_1)\bar{u}(x_2) - \Delta \bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}$$

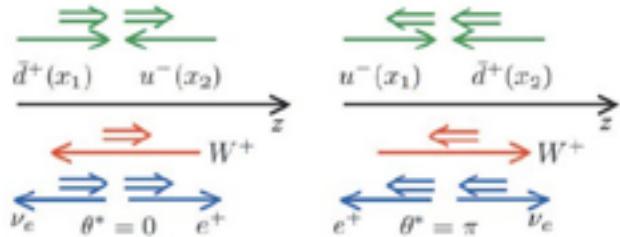
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$\Delta \bar{u}, \Delta \bar{d}$   
 $\Delta u, \Delta d$

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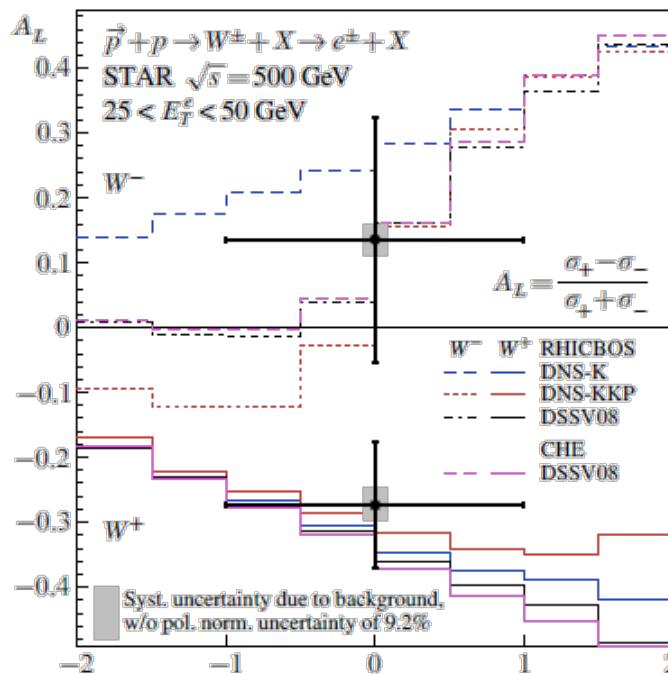
- 1<sup>st</sup> results published PHENIX: [arXiv:1009.0505](https://arxiv.org/abs/1009.0505)

STAR: [arXiv:1009.0326](https://arxiv.org/abs/1009.0326)

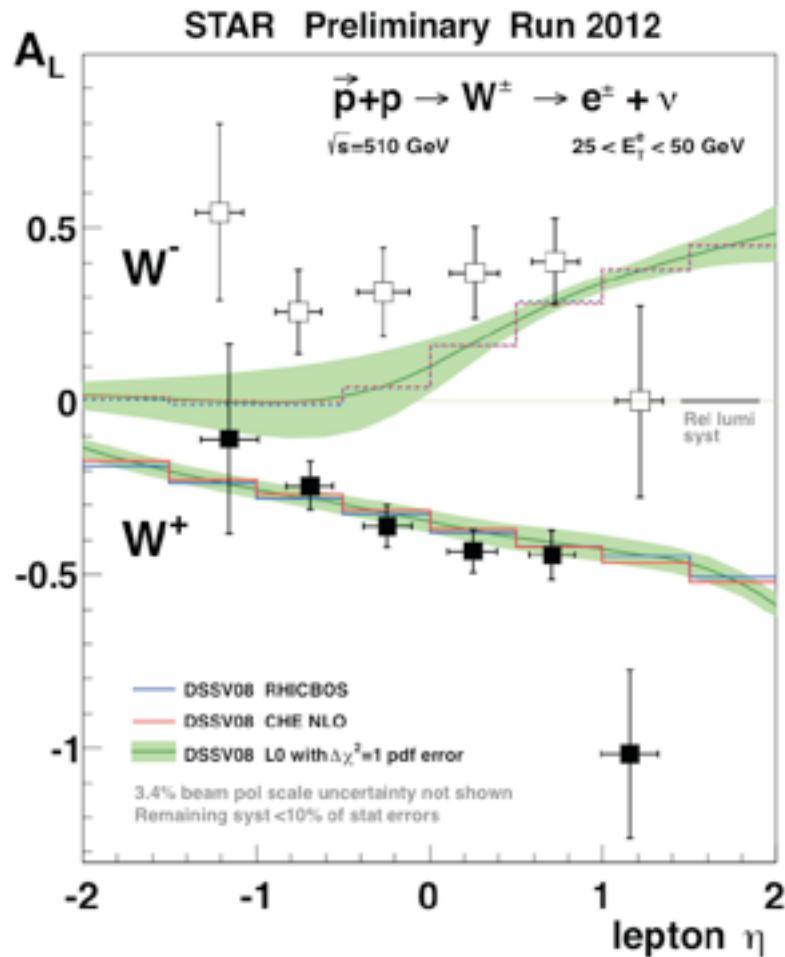
no impact on PDF fits yet

“proof of principle”

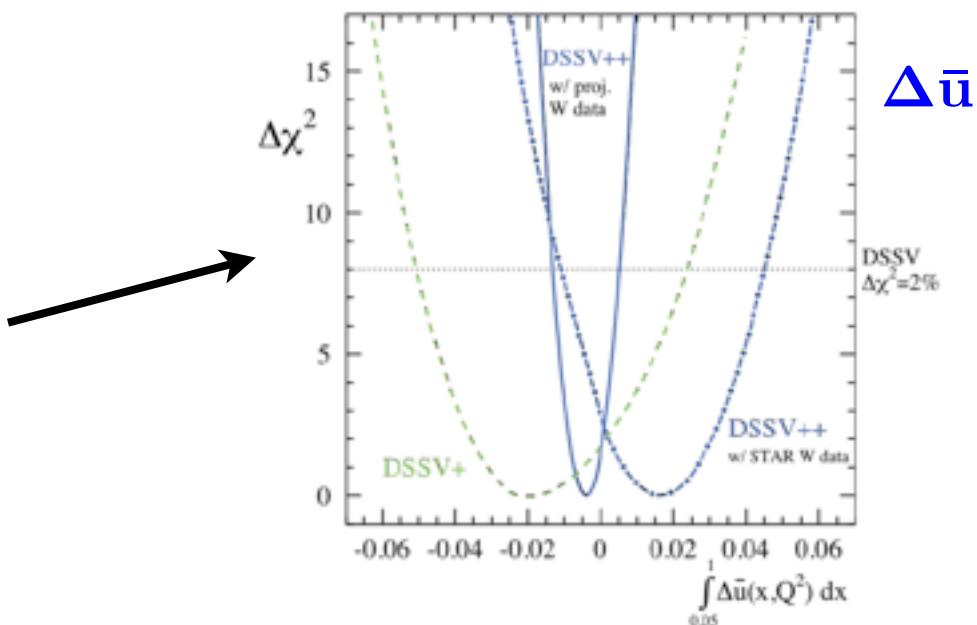
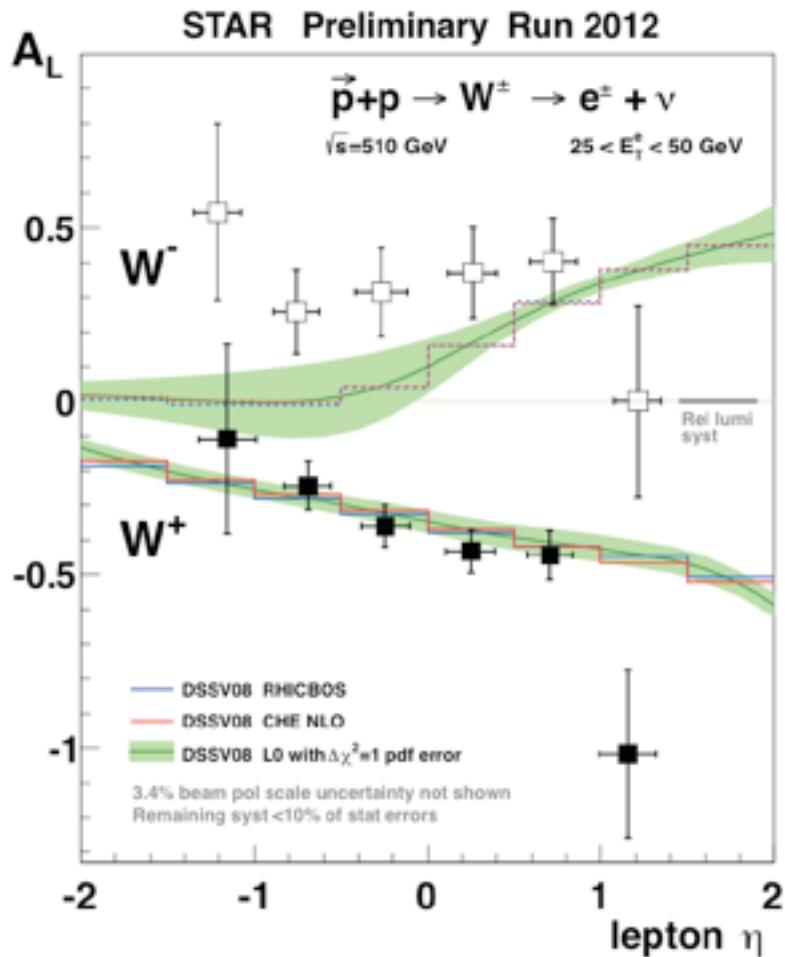
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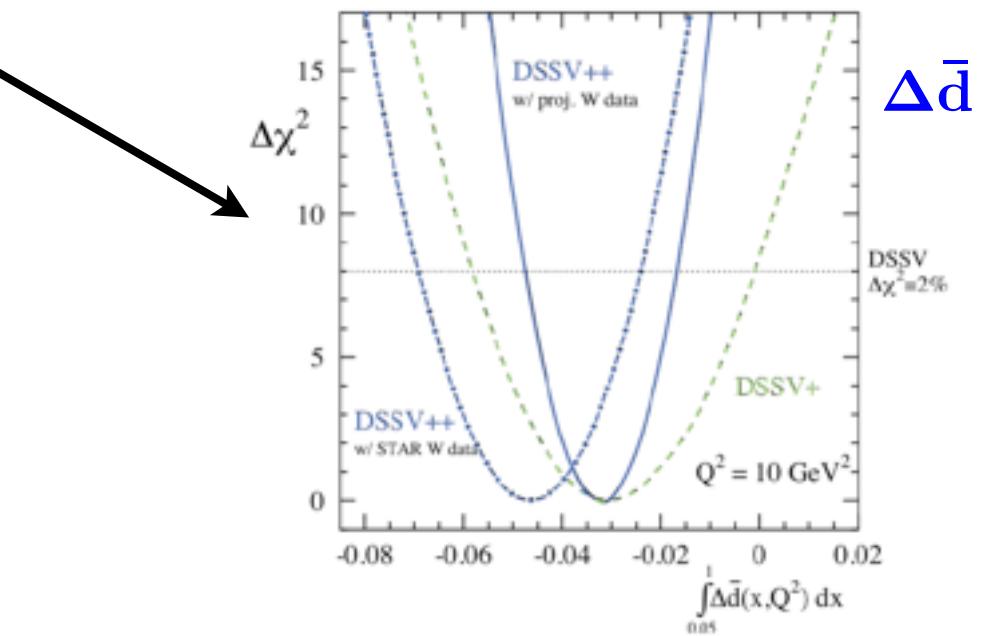
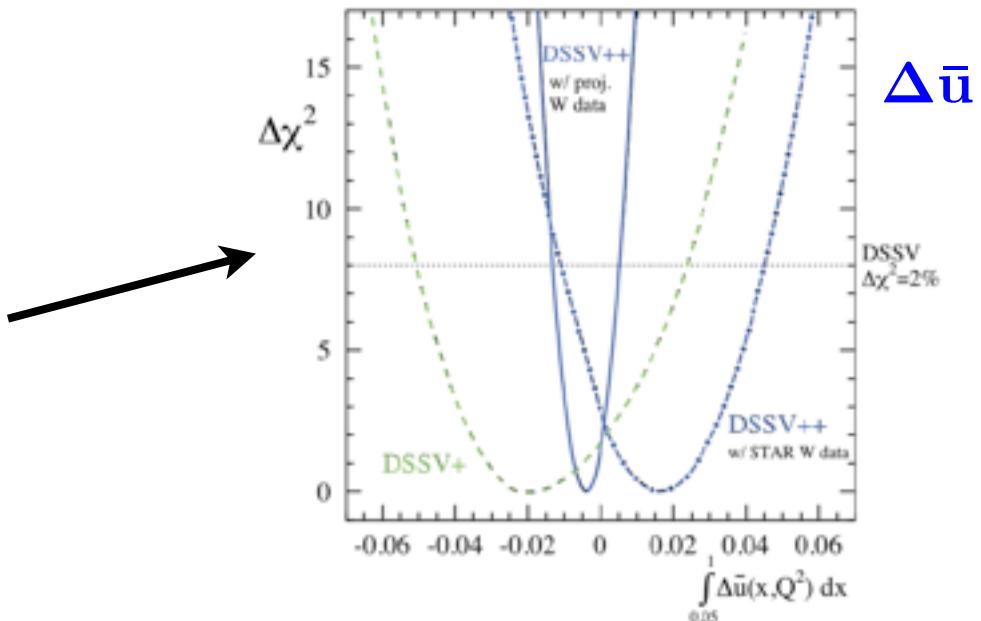
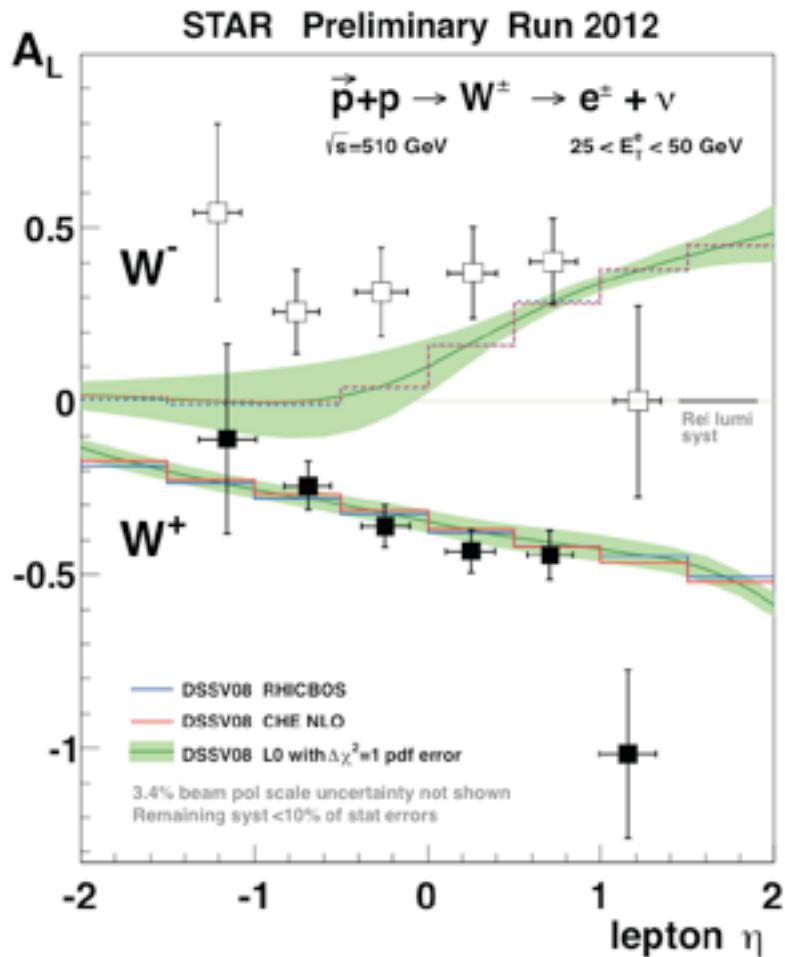
# new preliminary 2012 STAR data



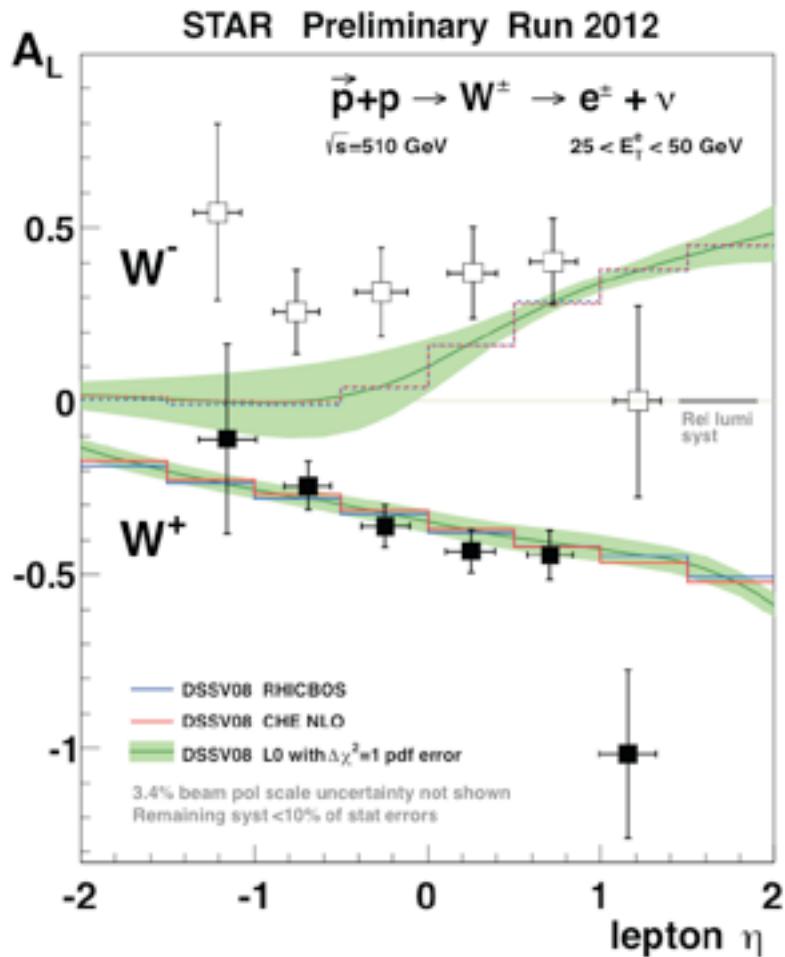
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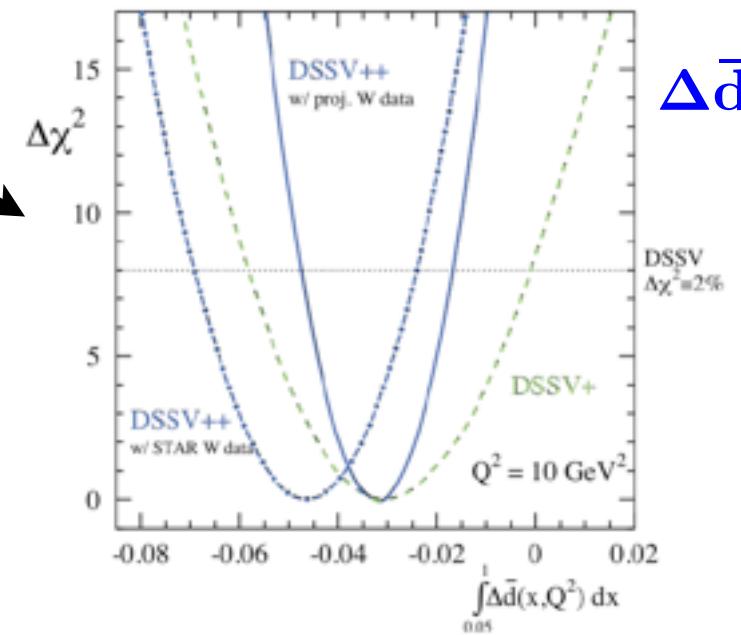
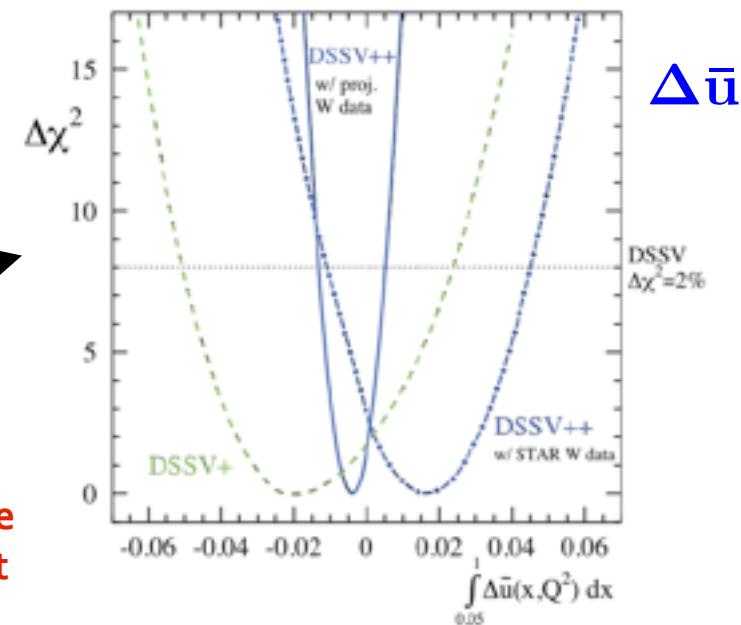
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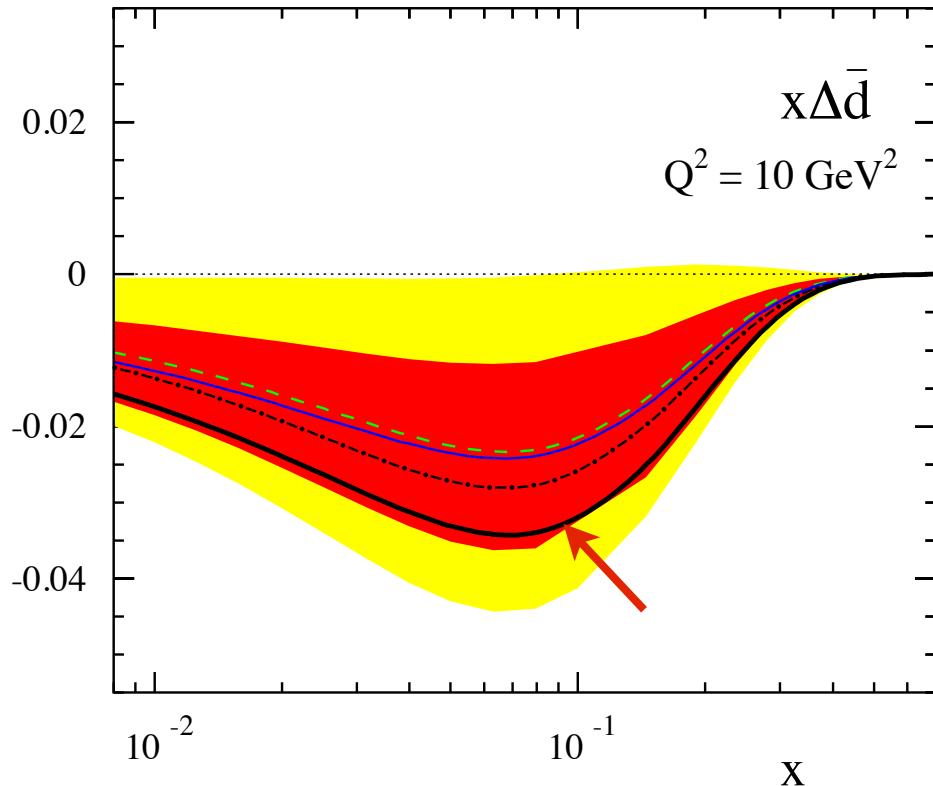
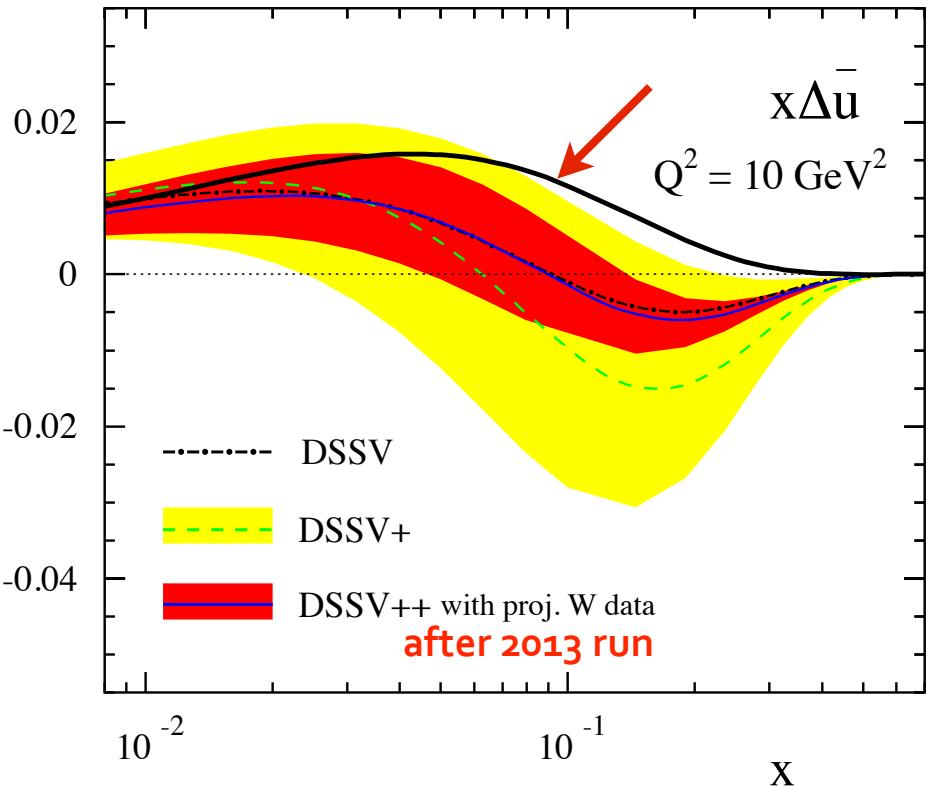
run 12 data  
already have  
a significant  
impact



much more to come from current RHIC run  
 (W program is a DOE performance milestone for 2013)

# impact in terms of $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$

still very preliminary !



- more detailed studies needed
- **tests what we know about sea quarks from SIDIS** (based on pion FFs)
- new fit points to rather sizable  $\Delta\bar{u}(x) - \Delta\bar{d}(x)$



# how to go from here?

RHIC will continue to further our knowledge of helicity PDFs

**but small-x ( $< 10^{-3}$ ) region is out of reach**

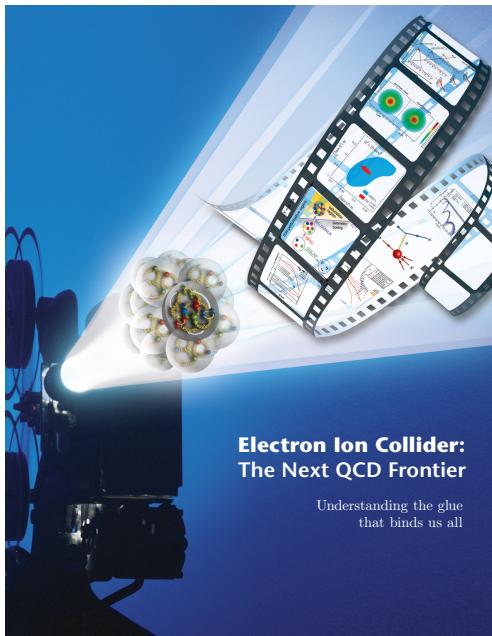
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logical step: an **Electron Ion Collider**



[arXiv:1212.1701](https://arxiv.org/abs/1212.1701)

lots of theory groundwork to be done



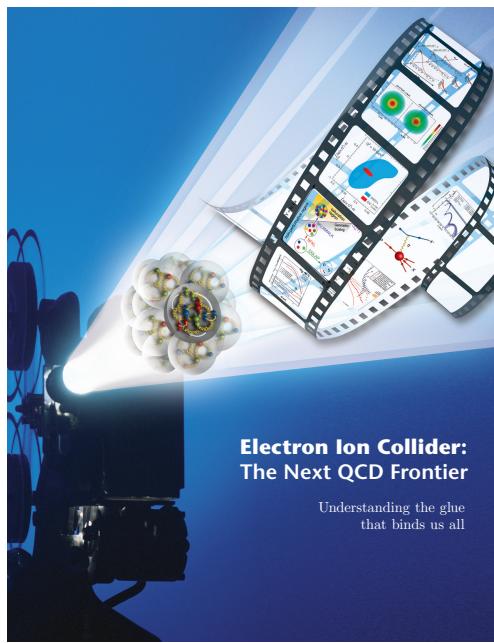
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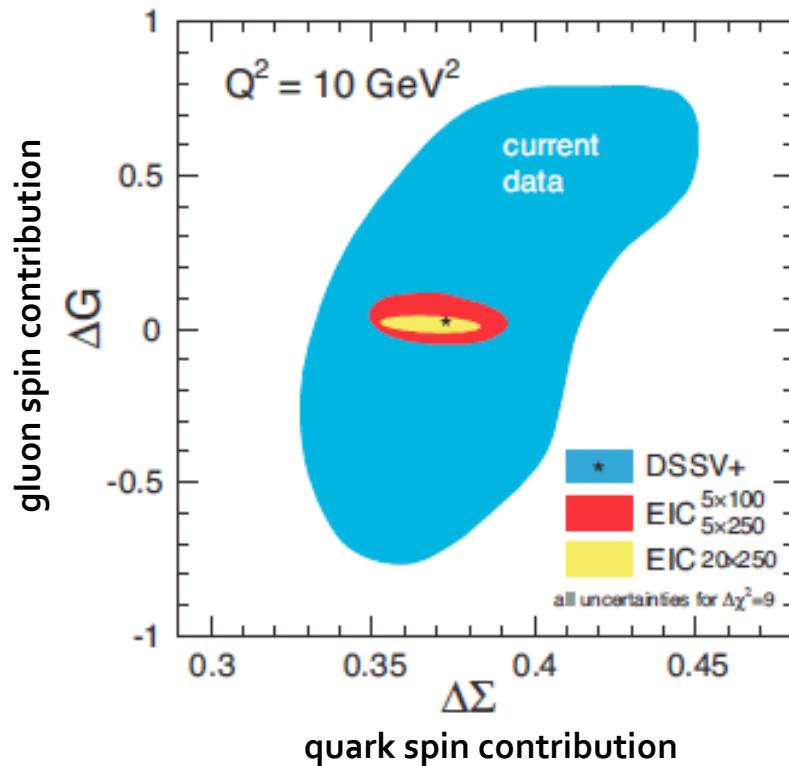
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appetizer: expectations for  $\Delta g$   
from Aschenauer, Sassot, MS



THE  
STORY  
OF  
SPIN

# The Story of Spin

## Shin'ichiro Tomonaga



It is a **mysterious beast**, and yet its practical effect prevails the whole of science. The existence of spin, and statistics associated with it, is the most subtle and **ingenious design of Nature** - without it the whole universe would collapse.

(from the preface)

exploring spin is of fundamental importance